ASSESSMENT OF GROUTS FOR CONSTRUCTABILITY AND DURABILITY OF POST-TENSIONED BRIDGES

A Thesis

by

SURESH KATARIA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2008

Major Subject: Civil Engineering

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Approved by:

Chair of Committee, David Trejo
Committee Members, Kenneth Reinschmidt
Catalin Teodoriu
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ABSTRACT

Assessment of Grouts for Constructability and Durability of Post-Tensioned Bridges.

(August 2008)

Suresh Kataria, B. Tech., Indian Institute of Technology, Guwahati, India

Chair of Advisory Committee: Dr. David Trejo

Post-tensioned (PT) bridge technology was first introduced in France in the 1930's as described in the post-tensioned concrete bridges: Anglo-French liaison report by Highway Agency and is widely used in Europe and the US. PT bridge technology is advantageous over other bridge-type structures due to its larger span-to-depth ratio and reduced construction costs and time. This technology however faces several challenges due to potential corrosion of the prestressing steel.

PT bridges constructed in the US during the 1970's used cementitious grouts to fill the empty spaces in the PT ducts in order to protect the strands from corrosion. This grout in the ducts was intended to protect the strands from being attacked by aggressive agents and to prevent corrosion. A mixture of ASTM Type I cement and water was used as the grouting material for construction of PT bridges. In Texas, four major PT structures have been in place for more than 10 years. Recent investigations of the PT bridges in Texas did not identify any strand failures. However, the visual inspections identified voids in many of the ducts, especially at the ends of the bridge spans. These

voids are believed to have been formed as a result of grout bleeding, poor grouting materials, and poor grouting techniques.

One of the main performance requirements sought from PT grouts is their ability to fill existing voids in the existing ducts. Currently, many prepackaged grouts are available for PT application that are reported to not bleed and provide better flowability as compared to the older ASTM Type I cement grout. However, the current standard specifications for approving grout materials have limited requirements for evaluating the "fillability" of these pre-packaged PT grouts. This research is being performed to provide modifications to the existing PT specifications such that PT repair grouts can be objectively assessed for fillability and long-term performance.

DEDICATED TO MY FAMILY

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NOMENCLATURE

ASCE	American Society of Civil Engineers
ASTM	American Society of Testing Materials
API	American Petroleum Institute
FHWA	Federal Highway Administration
PT	Post-Tensioned
PTI	Post Tensioning Institute
SCM	Supplementary Cementing Material
SEM	Scanning Electron Microscope
TxDOT	Texas Department of Transportation
w/c	Ratio of the weight of water to the weight of portland cement
w/cm	Ratio of the weight of water to the weight of all cementitious materials
w/p	Ratio of the weight of water to the weight of powder containing all cementing materials

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1. INTRODUCTION

1.1. Post-Tensioned Bridges

Post-tensioned (PT) concrete technology developed rapidly in the US during the 1960s (PTI 2003). This technology has applications in bridge construction due to its potential for larger span-depth ratios and reduced construction costs and time. In PT bridges, cementitious grout mixtures have been used to fill the PT ducts to protect the steel strands from corrosion. Material characteristics of these grouts can have significant impacts on the long-term durability of PT bridges. A tendon, as defined by Post-Tensioning Manual (PTI 2006), is *"a complete assembly of anchorages, prestressing steel and sheathing with post-tensioning coating for unbonded applications or ducts with grouts for bonded application."* A duct is a conduit to accommodate the prestressing steel and grout. Figure 1-1 shows a picture of tendons.

This thesis follows the style and formatting of *ASCE Journal of Construction Engineering and Management*.

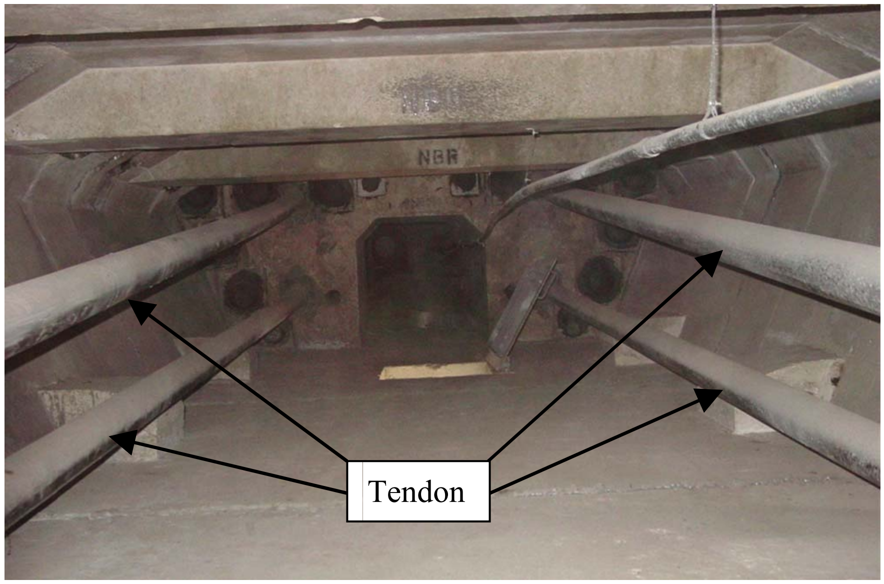

Figure 1-1. Inside view of a bridge box girder showing tendons.

1.2. Research Motivations

Several voids were recently identified in ducts of PT bridges. In many cases, these voids gave way to corrosion of the strands. This strand corrosion raised questions regarding the durability and safety of these bridges. The collapse of two bridges in Europe due to corrosion of steel strands raised concerns regarding the state of PT bridges in the US (ASBI 2000; NCHRP 1998; Sagüés et al. 2003). During the inspections of some PT bridges in the US, it was pointed out that the corrosion of steel strands was a result of voids in the PT ducts (FDOT 2001; Freyermuth 2001).

In most PT bridges a mixture of portland cement and water was used as a protective grout. Minimum concern was paid to the fluidity, bleeding, expansion, shrinkage and other material characteristics. These cement-water grouts are dimensionally unstable and can result in many voids. The strands can be exposed to the environment by the formation of these voids and can initiate corrosion of the steel strands in PT ducts (Figure 1-2). Use of suitable non-bleeding admixtures can improve the grout performance. Although improved results are possible, current standard specifications for approving grout materials typically have limited requirements for evaluating the fillability, which is a significant parameter for assessing PT bridge durability. As such, these specifications may require modifications.

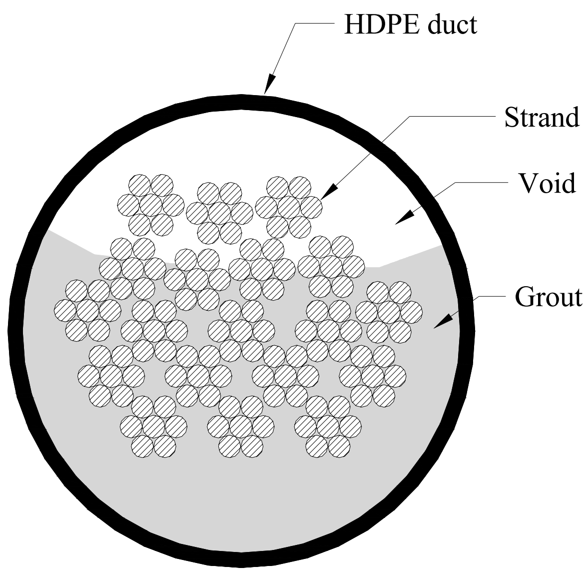

Figure 1-2. Typical tendon cross-section showing voids.

It is essential that high-performance grouts efficiently fill voids to minimize the corrosion of strands in PT ducts. A number of grouts are available on the market. Specifications or standards will be developed and/or existing standards or specifications will be modified to estimate the performance of these grouts in filling the voids in the PT ducts. This filling ability will be defined herein as fillability.

When PT bridges were originally built, a lack of standardized tests to measure fillability resulted in poor grouting materials. Currently, there is still no test available to measure the fillability of repair grout materials. Estimating fillability using a standard procedure and/or using the material characteristics can assist the PT bridge industry significantly by constructing more durable, longer-lasting bridges.

1.3. Objectives

The overall objective of the proposed research is to develop a performance specification and/or modify standard specifications for high-performance grouts. The research tasks to achieve this objective are as follows:

1. Characterize the following grout characteristics:
    a. **Fresh characteristics:** bleed, fluidity, fresh density, viscosity, and initial setting time
    b. **Hardened characteristics:** compressive strength, dimensional stability
    c. **Durability characteristics:** pH, chloride diffusivity
2. Develop a simple test procedure to determine the fillability of the grouts
3. Develop new specifications or modify the existing specifications to provide the durable grouts

2. LITERATURE REVIEW

To protect PT strands from corrosion, grout mixtures have been used to fill the void space between the strands and the inside of ducts. Various types of PT grouts are available on the market for post-tensioning systems. A literature review on the need for high-performance grouts, problems faced using normal portland cement grout, and critical grout characteristics has been performed and is presented next.

2.1. Grouts

Grouting is an established technique first used to fill cracks in rock strata to stop leakage of water. Most grouts used for this contain a mixture of clay, lime, or cement with water (Warner 2004a). As the demand for grouting increased, researchers developed several grouts and grouting techniques and applied these to various fields.

Applications of grouting in construction and repair of structures increased because of its ability to improve corrosion protection. This was the case for prestressed tendons and anchors on PT bridges. Grouting was also used to fill cracks and other defects in structural concrete members and for strengthening and improving soils and concrete materials. Grouting is an essential part of all PT concrete structures being constructed where the empty spaces in the tendon ducts are filled with grouts. Void spaces in highly congested PT tendons needs to be filled with a flowable cementitious grout to ensure filling and to minimize corrosion of the steel strands.

Portland cement based grouts have been used in the construction of PT bridges in the US since the 1950's (Schupack 2004). The main purpose of using the grout is to protect the steel strands from attack by external agents by providing a protective grout layer around the strands. Normal portland cement grout (a mixture of ASTM Type I cement and water) was initially used to fill the void spaces of PT ducts. Seemingly good flowability and economy were the main motivating factors behind using the portland cement grout. The Federal Highway Administration (2004) prepared the Post-Tensioning Tendon Installation and Grouting Manual and specified a limit on the maximum water-cement ratio[1] (w/c).

Various field investigations found unsatisfactory grouting of ducts in PT structures. The collapse of a segmental bridge in the UK in 1985 due to tendon corrosion raised a series of questions on the durability of these structures (Schupack 2004; Woodward 1980). Significant voids were found within the grouted ducts, which in many cases exposed the tendons to aggressive environments. It was determined that the portland cement grout used in the construction of these PT bridges bled, causing void formations. This material and the use of poor grouting practices, in some cases, also contributed to the formation of voids in the ducts (Freyermuth 2001).

[1] w/c is the ratio of the weight of water to the weight of normal portland cement.

Various researchers developed high-performance grouts using different types of mineral or chemical admixtures (Chaqui 2006; Hakansson et al. 1992; Hemmings and Cornelius 1991; Schokker et al. 2001) and these high-performance grouts are being used in the field for grouting ducts. However, there still exists a challenge to ensure proper grouting is accomplished in the field. The Post Tensioning Institute (PTI) developed a guide specification for grouting of PT ducts in the US (PTI 2003). The PTI guide specification provides guidelines for choosing PT grouts. Various grout manufacturers developed pre-packaged cementitious grouts conforming to these requirements. These prepackaged grouts are reported to exhibit improved volume stability, strength, and fluidity. However, the current Texas Department of Transportation's (TxDOT) specifications do not reflect the PTI specifications.

Recently, TxDOT inspected US 183 and the San Antonio 'Y' bridge. While these inspections found no failures of the PT tendons, the visual inspection identified incomplete grouting of the tendons, cracks in ducts, and corrosion of strands (Castrodale and White 2004). This research will provide specifications and test procedures such that PT repair grouts can be objectively assessed for fillability and long-term performance. It should be noted that the results from this research could be used for filling voids in new ducts or filling voids for the repair of ducts.

2.2. Fresh Characteristics

This section includes a discussion on the fresh characteristics of grout that can impact the durability of PT structures. The fresh grout characteristics that were considered in this research are presented in the following sections.

2.2.1. Bleed

Powers (1939) defined bleeding of a cement paste or mortar as the sedimentation of the suspended cement or sand particles. In other words, the individual cement or sand particles settle in the solution under the influence of gravity leaving the excess water on the top when the cement paste or mortar is at rest. Grout bleeding occurs in layers in which the upper layer of cement paste or mortar has higher w/c as compared to the lower layers. This results in weak, porous, and less durable paste at the upper surfaces. ASTM C940, *Standard Test Method for Expansion and Bleeding of Freshly Mixed Grouts for Preplaced-Aggregate Concrete in the Laboratory*, is the standard specification to evaluate the bleed of cement grouts.

A typical bleed test in a vertical channel is shown in Figure 2-1. The cylinder at the left contains freshly mixed grout. With time, settlement of cement particles takes place leaving excess water on the top. This is shown in the cylinder on the right. The grout level decreases with time in actual structures in a manner somewhat similar to the one shown in Figure 2-1.

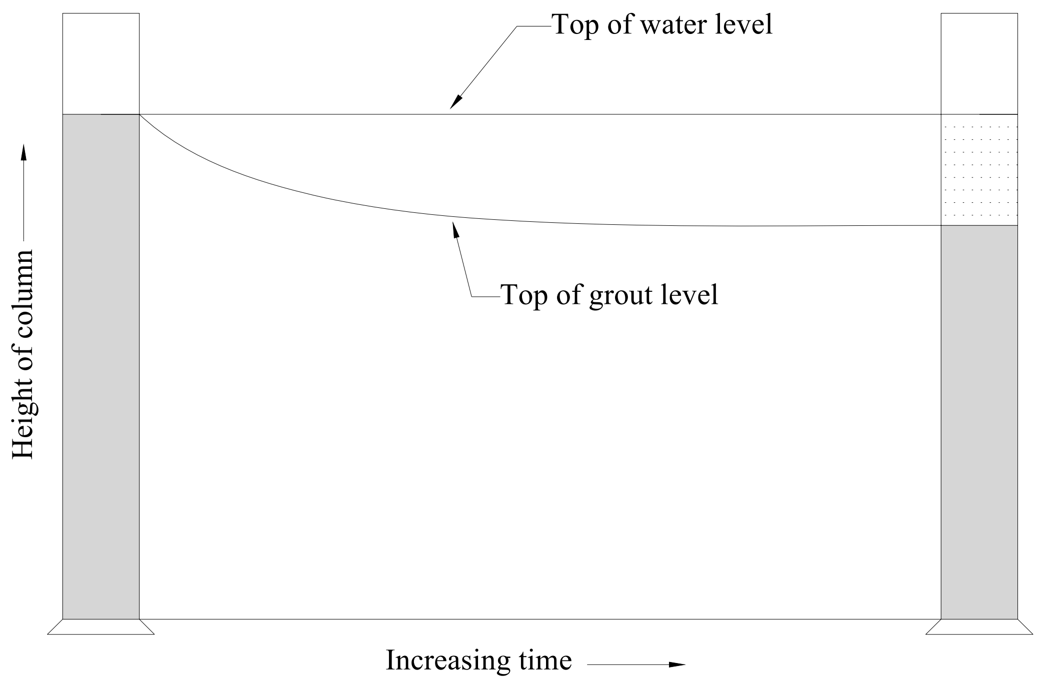

Figure 2-1. Illustration of a typical bleed process in graduated cylinder (ASTM C940).

Research conducted to study the effect of strands on grout bleed indicates that bleeding of grout in ducts for post-tensioning is largely influenced by the interstices between the king wire and the perimeter wires that act as capillary tubes (PTI 2003; Schupack 2004). This bleed water results in the formation of air voids in the PT ducts after the water evaporates or is reabsorbed into the grout (Earley 2004). A wick induced bleed test (Modified ASTM C940) is used to measure the bleeding in grouts when PT strands are present. The bleed water can be greatly reduced through good dispersion of the solids with high shear mixing. Non-bleeding properties of grouts can also be achieved by the addition of anti-bleeding admixtures to the cement grout (Schokker et al. 2001).

An investigation on the corrosion of in-place tendons on demolished bridges in California concluded that corrosion of strands was significant at major void locations (Schupack 2004). Schupack (2004) noticed that the void formation was mainly due to the bleeding of grout. He designed the "*Schupack pressure bleed test*" which was included in the PTI Guide Specification for Grouting of Post-Tensioned Structures (PTI 2001) as a grouting standard in 2001. This test is very useful in predicting the bleed resistance of a particular grout mixture. The recommended maximum allowable bleed for pre-packaged Class C grouts as given by Schokker et al. (2002) for a maximum tendon elevation change between 6 ft (1.8 m) and 100 ft (30.5 m) is zero percent bleed at air pressure of 50 psi (0.34 MPa).

Grout bleeding is an important parameter and needs to be measured for each grout mixture. Grout bleeding results in formation of voids in the PT ducts. Strands can be exposed to aggressive external environments due to formation of the voids and corrosion of these strands can occur. This void formation may, sometimes, reduce the effective grout cover on the strands which in turn reduces the time to initiation of corrosion of strands. The Schupack pressure bleed test should be performed if the maximum difference in elevation of longitudinal tendons is 6 ft (1.8 m) or for vertical tendons with heights of 20 ft (6.1 m) and more (PTI 2003).

2.2.2. Viscosity

Viscosity of a fluid is defined as a measure of the fluid's resistance to flow. A fluid can be "thick" or "thin" based on its ability to flow under a constant applied stress.

Water and alcohols are some examples of thin fluids whereas oil and gels are thick fluids. Viscosity is defined by considering laminar shear of fluid between two parallel plates (Figure 2-2). It is postulated that for uniform flow of fluids between parallel plates the shear stress between the layers is proportional to the velocity gradient (Ritchie 1965). To express this, the following equation is used:

$$\tau = \eta\left(\frac{dv}{dx}\right) \tag{2.1}$$

where τ is the shear stress, η is coefficient of viscosity, and $\frac{dv}{dx}$ is velocity gradient.

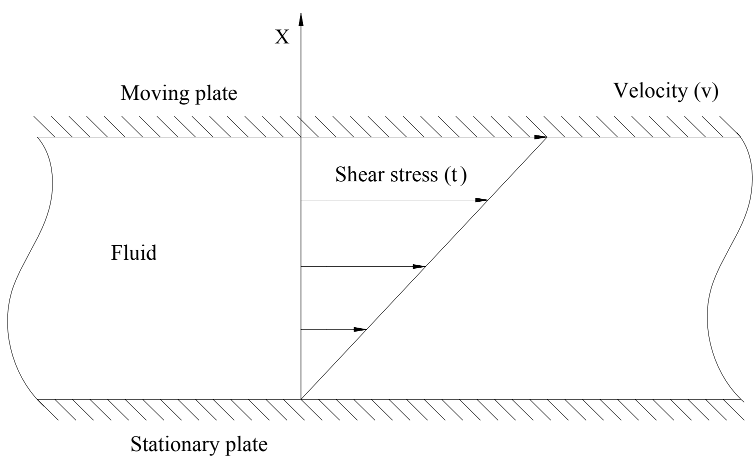

Figure 2-2. Laminar shear of fluid between two plates.

Fluids are categorized into two types based on their flow behavior. These are Newtonian and Non-Newtonian fluids. Water is a Newtonian fluid in which the stress is directly proportional to the rate of strain. Figure 2-3 shows the shear stress behavior of

Newtonian fluids. The slope of the shear stress-shear rate curve in Figure 2-3 represents the viscosity of fluids. A typical relationship between the shear stress (τ) and shear rate (γ) is shown by Equation 2.2:

$$\tau = \eta \gamma \tag{2.2}$$

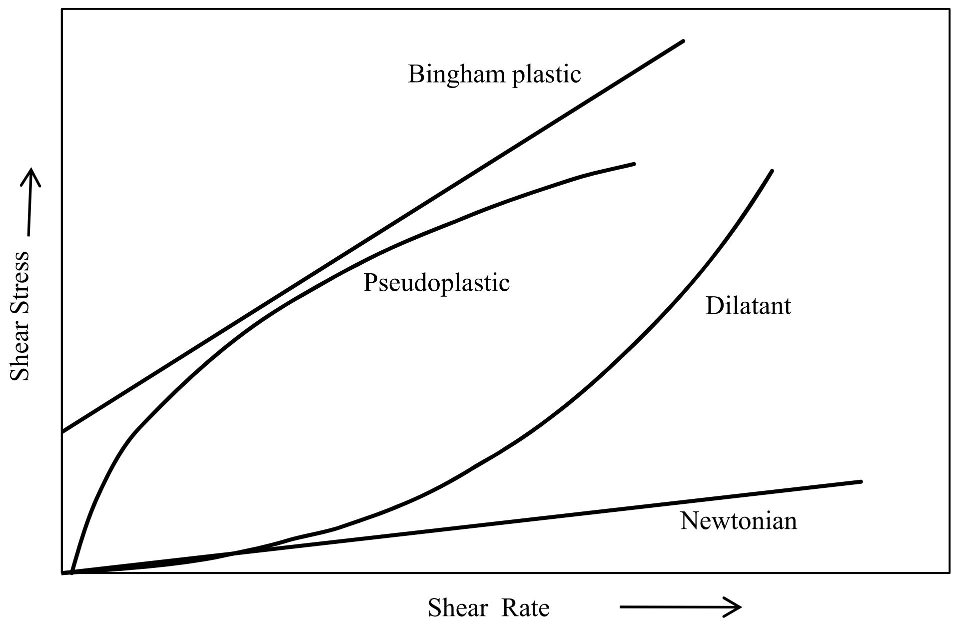

Figure 2-3. Newtonian and Non-Newtonian flow behavior.

A non-Newtonian fluid, on the other hand, exhibits a non-linear behavior. Non-Newtonian fluids are categorized by behavior type which is based on the fluid's change in viscosity in response to variations in shear rate. The three main types of flow behavior are: Bingham plastic, dilatant, and pseudoplastic (Ferraris 1999). Bingham fluids behave as a solid under static conditions and need a certain amount of stress, also known as "yield stress," to induce the flow. This type of behavior is shown in Equation (2.3) represents the Bingham model:

$$\tau = \tau_0 + \eta\gamma \tag{2.3}$$

where τ is shear stress, τ_0 is the yield stress, η is the viscosity and γ is the shear rate (Ferraris 1999). Dilatant fluids, as shown in Figure 2-3, are those in which the viscosity increases as the shear rate increases. Pseudoplastic fluids, on the other hand, exhibit a decrease in viscosity with the increase in shear rate.

Some fluids also exhibit change in viscosity with time under the influence of constant shear rate. Viscosity of Newtonian fluids does not change with time. Non-Newtonian fluids, on the other hand, exhibit a change in viscosity with time. Hence viscosity of these fluids is referred to as dynamic viscosity. Based on the nature of the change in viscosity, fluids are sub-divided into two categories: thixotropic and rheopectic (Ritchie 1965). Viscosity of the thixotropic fluids decreases with time when stress is applied. A rheopectic fluid's viscosity increases with time as the stress is applied (Ferraris 1999).

Most cement grouts exhibit a non-Newtonian flow behavior as they require a certain magnitude of yield stress or cohesion to make them flowable. These cementitious grouts can be categorized into pseudoplastic fluids as their viscosity reduces as the shear stress is increased. Because they require a positive stress of some magnitude to initiate movement they are also considered as thixotropic pseudoplastic fluids.

Hakansson et al. (1992) studied the rheology of cementitious grouts. The authors suggested that an increase in fineness increases the yield stress and the viscosity. The authors also noted that the rheological properties of a grout are affected by the paste water to cementitious materials ratio[1] (w/cm), fineness of the cement particles, the type of cement, mixing time, and cement hydration. Mixing time also plays a major role. Temperature and pressure also have an effect on viscosity. When temperature and pressure increases, viscosity decreases (Warner 2004). Hence, the mixing should be consistent in order to obtain reproducible properties.

Because the rheological properties of a grout are influenced by various factors it is important to measure viscosity characteristics of grouts in order to evaluate their flow properties. Because this test requires a comprehensive test procedure and an expensive setup, it is not advisable to perform this test in the field. Rather, a relationship between the viscosity and fluidity characteristics of grout can be determined by testing agencies or manufacturers as needed. Tests have been performed in this study to evaluate both the viscosity and fluidity characteristics and to study whether a correlation exists between the two.

2.2.3. Fluidity

A fluid is a substance that changes its shape when stress is applied. Fluids are categorized into two types based on their flow properties as discussed in section 2.2.2.

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[2] w/cm is the ratio of the weight of water to the weight of cement and other cementitious materials such as some mineral or chemical admixtures. It is different from the w/c as the cementitious materials include portland cement along with SCMs.

Newtonian fluids are the fluids in which the stress is directly proportional to the strain rate. Non-Newtonian fluids show non-linear behavior of shear stress to the strain rate and have higher viscosities due to which a positive pressure is required to pump such fluids through a duct (Warner 2004).

Grout fluidity is a measure of how fluid the grout mixture is and is a measure of the flowability of the grout. It is inversely proportional to the viscosity of a grout. This grout property is considered important as compared to other characteristics because it affects the fillability of the tendon (VSL 2002). The rheological behavior of all cementitious grouts is dominated by several physical and chemical factors such as w/cm, particle size distribution, fineness, addition and type of supplementary cementitious materials, and chemical admixtures.

Portland cement grout was extensively used in the construction of PT structures with the main objective of filling the voids. Pore spaces in PT ducts are typically small due to the presence of strands and low viscosity grouts are necessary. To achieve the desired flow that could fill void spaces in the PT ducts, the w/c was often adjusted to meet fluidity requirements. However, other characteristics are affected, mainly volume stability.

Challenges faced in grouting PT ducts due to the volume stability of grouts led researchers to develop grouts with better dimensional stability without the loss of fluidity. Various high-performance grouts were developed using ASTM Type I and III cements along with supplementary cementitious materials (SCM), water reducing admixtures, superplasticizers, and aluminum powders (Chaqui 2006; Hope and Ip 1988; Schokker et al. 2001). These grouts have been reported to perform better in terms of their fluidity and dimensional stability when compared with traditional portland cement grouts.

Increasing demand of high-performance grouts in PT applications led various organizations to develop pre-packaged PT grouts. These pre-packaged PT grouts eased the on-site grout mixing requirements and are believed to contain one or more chemical and mineral admixtures. These grouts typically exhibit thixotropic, pseudoplastic flow behavior (Yahia and Khayat 2003) and the conventional method of evaluating their flow properties (ASTM C939: *Standard Test Method for Flow of Grout for Preplaced-Aggregate Concrete* (*Flow Cone Method*)) does not address this true flow behavior.

TxDOT issued specifications for measuring efflux time of thixotropic grouts (Tex-437-A). This TxDOT standard is also known as the modified ASTM C939 test procedure to measure the efflux time of thixotropic grouts and is also contained in the PTI grout specification manual (2003). According to the Method 2 of Tex-437-A standard specification, the flow cone is filled with freshly mixed grout up to the top and the time it takes to flow the initial 2.11 pints (1000 ml) grout from the ½ inch (12.7 mm) orifice is measured as the grout's efflux time.

Because most prepackaged grouts are thixotropic grouts, the method 2 of Tex-437-A standard can evaluate the fluidity characteristic of the grout more accurately. Also, it is a simple test procedure and can be conducted in the field for each batch of mixture.

Therefore, this standard may be applicable to evaluate the efflux time of grout mixtures in the field.

2.2.4. Wet Density

Quality control of freshly prepared grouts is essential to ensure proper filling of PT ducts. An increase in the water content of the grout can initiate bleed which can led to formation of voids in the PT ducts. The American Petroleum Institute (API) provides Specification RP 13B-1, *Recommended Practice Standard Procedure for Field Testing Water-Based Drilling Fluids to measure specific gravity of grouts*. Also referred to as the Baroid Mud Balance test, this test is used to measure the specific gravity of drilling fluids. Although this test procedure is used to measure the density of grouting fluids for drilling purposes, it can also be used as a good quality control device to provide information on the water-powder ratio[1] (w/p) of the mixture in the field prior to placement in the duct.

The Baroid Mud Balance provides a measure of the consistency of the grout produced in the field (Clark and Ganz 2002). A comparison of the wet density of the freshly mixed grouts at the inlet (mixer) and outlet (grout vent) of the grout pump is a means of verifying the quality of field produced grout. Ideally, the density of the grout at the outlet should never be less than the density at the inlet of grout pump. Similar

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[3] w/p is the ratio of weight of water to the weight all cementing materials included in powder. It is different from w/cm as other than the cementitious materials this powder may contain some aggregates which are unknown as the PT grout materials are proprietary.

densities ensure no sedimentation of the grout. According to the Federal Highway Administration's (FHWA) Post-Tensioning Tendon Installation and Grouting Manual, the consistency and density of field produced, pre-packaged, thixotropic grouts can be checked by measuring the grout density at both the mixer and grout vent (FHWA 2004).

2.3. Hardened Characteristics

This section includes a discussion on the hardened characteristics of grout that can impact the durability of PT structures. The hardened characteristics that were considered in this research are presented in the following sections.

2.3.1. Compressive Strength

A normal portland cement grout (ASTM Type I cement and water) was used in most PT bridges constructed in the Texas until approximately 2000. Grout bleeding and void formation was found to be the main cause of corrosion of PT strands in most of these PT bridges. A careful evaluation of the grouts' fresh properties (bleed and fluidity) would provide valuable information for determining proper grouting requirement and materials for successful future post-tensioning. Compressive strength, on the other hand, does not provide a direct measurement of a grout's ability to fill the voids in PT ducts. Instead, this property is considered to provide an indication of the grout quality with respect to its bond and shear strength, and possibly an indication of its durability.

2.3.2. Dimensional Stability

Various physical factors such as surrounding temperature, humidity, and chemical factors such as carbonation shrinkage, sulfate attack, and alkali-aggregate reactions affect the dimensional stability of the hardened grout specimens (Kosmatka et al. 2002). Hence, it is important to measure the effect of these physical and chemical factors on the volume stability of the cementitious grouts.

Shrinkage of cement grouts in PT structures is an important durability issue. This volume change of the grout can result in formation of voids in PT ducts. Drying shrinkage in portland cement grout is affected by its water content. As the water content is lowered, drying shrinkage is reduced but the flow properties are also affected (grout become less fluid as the water content is lowered). Studies have shown that the addition of SCMs such as fly ash also reduces the drying shrinkage and increases the flow. Chemical admixtures, on the other hand, have been reported to have little or no effect on the drying shrinkage of cement paste (Kosmatka et al. 2002).

Grout cracking in the PT ducts is another important parameter that needs to be assessed. If cracks develop in the hardened grout, the PT strands can be exposed to the external environment and corrosion can initiate. Cracking in the hardened grout can be either temperature cracking or drying shrinkage or due to external agents such as sulfate attack. Changes in the relative humidity and temperature can cause grout cracking if the hardened grout is directly exposed to the environment which may be the case with cracked ducts. Cracking due to the drying shrinkage can be controlled by controlling the curing process after placement. Cracking due to sulfate attack can be controlled by selecting suitable cement and admixtures (Mindess et al. 2003).

Various pre-packaged, high-performance grouts that have been developed for post tensioning applications are believed to be non-shrinking grouts. A careful evaluation of the volume change of these grouts is required to improve the durability of PT structures.

2.4. Durability Characteristics

This section includes a discussion on characteristics that can impact the durability of PT structures. The durability characteristics that were considered in this research are presented in the following sections.

2.4.1. Chloride Diffusivity

In PT bridges, corrosion of strands can be a serious problem as corrosion can reduce a bridge's performance and safety. Strand corrosion in PT structures has been identified as being mainly due to the use of poor grouting practices and materials. Generally, the PT ducts are filled with cementitious grout to prevent the strands from being exposed to aggressive corrosive agents. But due to the use of dimensionally unstable grout and poor grouting practices, ducts may not be filled fully, resulting in voids and exposure of strands to these aggressive environments. Moreover, the use of precast elements and inadequate detailing of joints and drainage in modern bridges can make them more susceptible to corrosion (Gallagher 1989; Goodwin 2002). Woodward (1980) investigated 12 bridges in the UK and found voids in the ducts of 10 bridges.

In many cases, strand corrosion is initiated by the presence of water and chlorides near the strands. Chlorides can penetrate through the grout. This ingress of chlorides through uncracked grout is diffusion controlled and depends on the apparent chloride diffusion coefficient, D_a. The chlorides diffuse from a place of higher concentration to a place of lower concentration. This is described by Fick's Second Law (Mindess et al. 2003):

$$\frac{\partial C}{\partial t} = D_a \frac{\partial^2 C}{\partial x^2} \tag{2.4}$$

where: C = chloride concentration, mass %,

t = exposure time, seconds,

D_a = diffusion coefficient, inch^2/seconds (m^2/seconds),

x = depth below the exposed surface, inch (m).

The chloride concentration at any depth and any time can be obtained by solving this differential equation. ASTM C1556-03, *Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion*, (ASTM C1556-03) provides a test procedure to determine the diffusion coefficient of a cementitious material. The chloride ion concentration at any depth x and time t, $C(x,t)$ as explained in ASTM C 1556-03 is given by the Equation (2.5):

$$C(x,t) = C_s - (C_s - C_i) \times erf\left(\frac{x}{\sqrt{4D_a t}}\right) \tag{2.5}$$

where:

C_s = chloride ion concentration at the surface of a concrete specimen, mass %,

C_i = initial chloride-ion concentration of the specimen, mass %,

erf = error function described in equation (2.6) below

$$erf(z) = \frac{2}{\sqrt{\pi}} \times \int_0^z \exp(-u^2)du \tag{2.6}$$

where z refers to the expression $\frac{x}{\sqrt{4D_a t}}$ and u is a regression variable. The value of this error function corresponding to the specific depth x and time t can be obtained from standard mathematical reference books (Beyer 1978).

It should be noted that the rate of transport of chlorides in a round duct will be different than that shown in Equation 2.5. Diffusion in a round duct is two-dimensional (Equation 2.5 is for one-dimensional flow) and is given by the equation 2.7 (Poulsen and Mejlbro 2006):

$$\frac{1}{D_a}\frac{\partial C}{\partial t} = \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \tag{2.7}$$

Because the current ASTM standard (ASTM C 1556) to measure chloride diffusivity of concrete specimens assumes one-dimensional rate of transport of chlorides, the one-dimensional flow rate is assumed to evaluate diffusivity of PT grouts.

Because grouts provide a protective cover to the strands, the resistance of these grouts to the transport of chlorides is critical. Because of this, diffusion rates will be determined for grouts assessed in this study. It should be noted that diffusivity measurements are relatively time consuming and it is anticipated that this testing will not be required for all grout placements.

2.4.2. pH

In PT bridges, the strands are surrounded by grout which is supposed to protect the strands from being exposed to aggressive agents. In a normal PT duct, the embedded strand is covered by the grout. The pore spaces in the paste contain a highly alkaline solution (with a pH higher than 12) which inhibits the corrosion of the strands by creating a passive environment for the strands (Locke 1986).

Hence, there is need to determine the pH of the pore solution of grouts because lower pH values increase the chance of corrosion of PT strands. Because there are no ASTM standards available to test the pH of the pore solution it is difficult to measure. In this research, the pH of the pore solution was assessed using the method explained by Barneyback and Diamond (1981) and is discussed later.

2.5. Fillability

Many tests are available to evaluate the fresh characteristics of PT grouts. These tests include efflux time, bleed, viscosity, and wet density. However, there are no established standard specifications that can estimate to what extent a freshly prepared PT grout can fill voids in PT ducts. Tests such as the bleed test (or wick-induced bleed test) only attempt to explain whether the grout to be used in PT applications will result in void formation. The flow cone test provides a measure of the fluidity, not fillability. Note that a concrete mixture with a ½ inch (12.5 mm) maximum size aggregate can exhibit high fluidity but would not fill the voids in a PT duct. No test method or standard is currently available to assess the fillability of grouts through small pore size openings such as that found in PT ducts.

Various studies have been conducted on grouts for purposes of injecting them in joints or cracks of rock strata for geotechnical purposes. Researchers have shown that these grouts cannot pass through a specific aperture and put limits on the minimum aperture through which the grout can be injected (Amadei 2000; Moon and Song 1997). Eriksson et al. (2000) have shown that this aperture size varies for various grouts and an evaluation of the minimum aperture of each grout is necessary to find out the penetrability of that particular grout.

Eriksson and Stille (2003) developed a test method to measure and evaluate the penetrability of cement based grouts. The test method includes a penetrability meter that gives parameters for making grouting penetration predictions. The parameters obtained from the penetrability meter test are the minimum and critical aperture of the grout. The authors defined the minimum aperture as the aperture through which no grout can pass and the critical aperture as the opening through which an infinite volume of grout can flow. Because the particle size and other characteristics of various grouts differ due to their different production methods, the minimum and critical aperture limits differ significantly with the type of grout.

In this study, a fillability test setup was developed. This setups is similar to the penetrability meter developed by Eriksson and Stille (2003). The objective behind using this fillability meter is to differentiate and/or assess various pre-packaged PT grouts in terms of their performance to fill small voids in PT systems. The fillability meter design and test procedure is discussed in the next section.

2.6. Research Significance

Voids in PT bridges are a potential cause for accelerated strand corrosion and bridge failure. This research addresses this challenge by assessing key grout characteristics and developing specifications such that high-performance grouts can be used to fill PT ducts. Also, a newly developed fillability test could provide a new standard for field testing. These tests will assist engineers in predicting the performance of grouts not only when repairing existing structures, but also during the construction of new PT bridges. The successful completion of this research is important for the economical and safe repair and construction of bridges.

3. EXPERIMENTAL PROGRAM

This study deals primarily with evaluating various fresh, hardened, and durability characteristics of pre-packaged grouts and developing standard specifications to select PT grout for grouting new and existing PT bridges. Various test variables were identified and evaluated to assess the fresh, hardened, and durability characteristics of the pre-packaged PT grouts.

This section comprises descriptions on the various test variables used for the research, a brief discussion of the test matrix, details of the mixing procedures performed, and a discussion of the test procedures used in the research. This section also includes the design and proposed procedures for the fillability test setup developed as a part of this research to evaluate the grout's filling ability inside a PT duct.

3.1. Test Variables

Four variables were identified and the experiments were performed to study the effects of each variable on the grout characteristics. A detailed description of the test variables is presented in the following sections.

3.1.1. Grout Types

The specification developed by PTI provides minimum performance requirements for a specific grout to be used in protecting and bonding tendons in PT applications (PTI

2003). According to the PTI specifications (2003), grouts are divided in four classes based on the material specifications and field requirements. These classes are designated as classes A, B, C, or D. Class A is the normal portland cement grout with a maximum w/c of 0.45 and is intended to be used in non-aggressive exposure environments. Class B grouts contains SCM's and is for use in aggressive exposure environments. Class C grouts are pre-packaged, PT grouts that can be used for both aggressive and non-aggressive exposure conditions (PTI 2003). Class D grout is a specially prepared PT grout to be use in specific conditions where the grout performance characteristics can be carefully controlled.

Class A grout has been used in the construction of most existing PT bridges constructed before the year 2000 and does not exhibit thixotropic properties. Class B, C, and D grouts contains admixtures and may be thixotropic (PTI 2003). Commercially available prepackaged grouts are Class C grouts and are also referred to as high-performance grouts. Three commercially available high-performance grouts that are being tested for this research are identified as grouts Class C-1, C-2, and C-3. These three grouts and a Class A control grout are shown in Table 3-1 along with their respective identification.

Table 3-1. Pre-packaged grouts along with their identification labels.

Grout	ID
ASTM Type I cement	Class A
Master flow 816 grout	Class C-1
Sika 300PT grout	Class C-2
Euco Cable grout PTX	Class C-3

Because the contents of these pre-packaged PT grouts are unknown, the ratio of water to all pre-packaged grout ingredients will be referred to as the water-powder ratio (w/p). Table 3-2 shows the manufacturer's recommended w/p for the grouts considered in this research.

Table 3-2. Recommended w/p for the four grout types.

Grout	Recommended w/p
Class A	0.44
Class C-1	0.30
Class C-2	0.26
Class C-3	0.27

3.1.2. Mixer Types

The post-tensioning of new bridges requires a large volume of the grouts (approx. 8 ft^3or 0.23 m^3 of grout required for a standard 150 ft long PT duct). Hence, a large field grout mixer with high shear action is desirable. A variety of high-shear mixers and colloidal mixers are available for this purpose. In repairing the voided ducts of existing PT bridges, a relatively small quantity of grout (less than 1 ft^3 or 0.028 m^3) is often required. In these cases the larger field grout mixers may not be applicable for repairs and common practice is to prepare smaller quantities of grouts with hand drills. Two models of portable corded drill mixers were considered in this research. A need for a mixer that could impart high-shear action to achieve the best possible mixing in the shortest time was desirable. Two corded drill mixers with rotating speeds of 2500 and 4000 rpm (identified as M1 and M2 mixers respectively) were selected to evaluate the effect of mixer speed on the characteristics of grout. Figure 3-1 shows the mixing paddle used with M1 and M2 mixers.

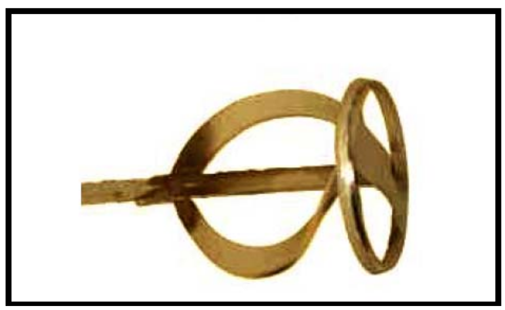


Figure 3-1. Mixing paddle used with M1 and M2 mixers.

In addition to the standard drill mixers, two hand-held high shear mixers, manufactured by Desoi, of Germany were procured and used to produce grout mixtures. Figure 3-2 shows the high shear mixer by Desoi. These high shear mixers were used to mix various grouts but it was found that these mixers overheated when mixing relatively small volumes. Because of this, it was decided not to further evaluate grout characteristics mixtures with these high shear mixers.

Figure 3-2. High shear mixer from Desoi.

3.1.3. Mixing Volume

While performing experiments it was observed that mixing volume may have an effect on the efflux time of the grout. Therefore the volume of the mixture was also considered as a potentially influencing variable. The mixture volume ranges used in this research were 0.25, 0.50, and 0.75 ft^3 (0.0071, 0.0142, and 0.0213 m^3) respectively.

3.1.4. Water-powder Ratio

Maintain exact w/p when large batches of grout are being mixed in the field is difficult. Because the fresh characteristics of many pre-package grouts are sensitive to changes in w/p and the w/p can influence the hardened characteristics of the grout, the performance of grouts as a function of w/p was also investigated. All three grout manufacturers specify a recommended w/p for their product. These different w/p values and their influence on grout characteristics were also investigated.

To evaluate the sensitivity of w/p on grout characteristics, the w/p was varied from −5% to +15% of the recommended w/p. Table 3-3 shows the w/p values used in this research. The test matrix for this research is shown in Table 3-4. This table shows all test variables evaluated to study the grout characteristics.

Table 3-3. w/p for all four grouts used in experiment.

Grout	5% lower w/p	Recommended w/p	15% higher w/p
Class A	0.41	0.44	0.51
Class C-1	0.27	0.30	0.35
Class C-2	0.25	0.26	0.30
Class C-3	0.26	0.27	0.31

Table 3-4. Test matrix used in the research.

Mixer Type	Grout Type	w/p	Mixture Volume ft^3 (m^3) 0.25 (0.007)	0.5 (0.014)	0.75 (0.021)
M1	Class A	0.42	√	√	√
		0.44[a]	√	√	√
		0.51	√	√	√
	Class C-1	0.29	√	√	√
		0.30[b]	√	√	√
		0.35	√	√	√
	Class C-2	0.25	√	√	√
		0.26[c]	√	√	√
		0.30	√	√	√
	Class C-3	0.26	√	√	√
		0.27[d]	√	√	√
		0.31	√	√	√
M2	Class A	0.42	√	√	√
		0.44[a]	√	√	√
		0.51	√	√	√
	Class C-1	0.29	√	√	√
		0.30[b]	√	√	√
		0.35	√	√	√
	Class C-2	0.25	√	√	√
		0.26[c]	√	√	√
		0.30	√	√	√
	Class C-3	0.26	√	√	√
		0.27[d]	√	√	√
		0.31	√	√	√

Note:

a = Recommended w/p for Class A
b = Recommended w/p for Class C-1
c = Recommended w/p for Class C-2
c = Recommended w/p for Class C-3
√ = Indicates grout was evaluated as part of this research

3.2. Mixing Procedure

It is important to achieve a uniform mixing procedure and prepare the grout the same way to achieve repeatability. The grouts were mixed using one of the mixers (M1 or M2) discussed in section 3.1.2. The mixing was performed in a 10 gallon (38.85 liter) cylindrical containers for mixture sizes greater than 0.50 ft^3 (0.0142 m^3) and in a 5 gallon (18.93 liter) cylindrical container for mixture sizes of 0.25 ft^3 (0.0071 m^3). The following mixing procedure was used:

- The appropriate amount of water was measured and added to the container and the grout was added slowly to the water within the first 30 seconds while the mixer was rotated at a slow rpm.
- A stop watch was started when half of the grout was added to the water; the mixer was rotated at its maximum mixing speed after all grout was added to the water.
- The mixer was stopped after 1 minute and the dry grout was scraped from sides of the container. The mixer was not stopped for more than 30 seconds.
- The grout was then remixed for additional 4 minutes.

All mixes were prepared at a room temperature of 75±4 °F (23.8±2.3 °C). The mixing time for each grout was determined based on the efflux time values. Required mixing times for the grouts are shown in Table 3-5.

Table 3-5. Time of mixing with mixers for all four grouts.

Grout	Mixing time (minutes)
Class A	5
Class C-1	5
Class C-2	6
Class C-3	20

3.3. Tests Performed

Table 3-6 shows the tests that will be conducted as part of this research. The test standards that will be used for each test are also shown in the Table 3-6. Brief descriptions of each test procedure including the standard followed are presented next.

Table 3-6. Test procedures and the corresponding standards followed.

Tests	Standard followed	Description	Number of samples
Fluidity	Modified ASTM C939 (Tex-437-A)	Test of fresh grout characteristic	1 per mixture
Wick-induced bleed	Tex-441-A	Test of fresh grout characteristic	3 per mixture
Compressive strength	ASTM C942	1, 3, 7, 28, 56 day strength test	3 per test age
Volume Change	ASTM C1090	1, 3, 7, 14, 28 day test	1 per mixture
Initial Set	ASTM C953	Test of fresh grout characteristic	1 per mixture
Mixture density	Baroid Mud Balance	Test of fresh grout characteristic	1 per mixture
Chloride diffusion	ASTM C1556	Hardened	3 per mixture
Viscosity	Brookfield Rheometer	Test of fresh grout characteristic	1 per mixture
pH	None	Hardened	1 per mixture

3.3.1. Wick-Induced Bleed

The wick-induced bleed test was performed on all grout types following TxDOT standard, Tex-441-A: *Wick Induced Bleed Test of Freshly Mixed Grouts,* and is similar to the PTI's wick induced bleed test (PTI 2003). All grouts with three different w/p, three different mixture volumes, and two mixer types were tested to study the effect of w/p, mixture volume, and mixer type on the rate and amount of bleeding. Three samples per grout mixture were evaluated based on the TxDOT specifications (Tex-441-A). Figure 3-3 shows the wick-induced bleed test. The final bleeding was determined by evaluating the average of three bleed cylinders using the following equation:

$$\text{Final Bleeding, \%} = \frac{V_w \times 100}{V_s} \tag{3.1}$$

where V_w is the volume of bleed water in pints (ml) and V_s is the volume of sample at the beginning of the test in pints (ml).

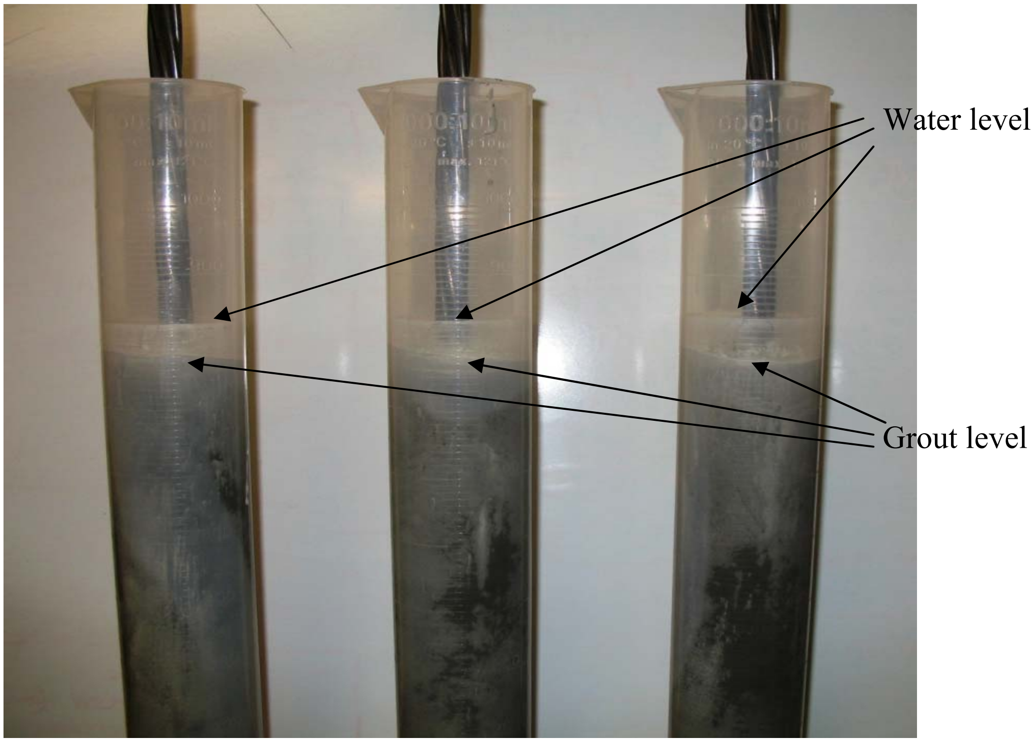


Figure 3-3. Wick-induced bleed test according to TxDOT standards (Tex-441-A).

3.3.2. Viscosity

Viscosity is an important flow characteristic that should be evaluated to assist in predicting the flow of grout inside a PT duct. There has always been the issue of whether a low or high viscosity grout will perform better in filling voids inside PT ducts. Findings from Schupack (2004) determined that a more viscous, thixotropic grout will achieve better water retention capacity.

The viscosity tests were performed using a Digital Programmable Rheometer by Brookfield Engineering. This test used three pieces of equipment. A DV-III+ Digital Programmable Rheometer (Figure 3-4) was used to measure the viscosity of the grout with a spindle attached to the rheometer. A Model D Helipath Stand, also by Brookfield

Engineering (Figure 3-4) was used to raise and lower the rheometer to obtain viscosity measurements at different depths and a temperature probe was used to measure the temperature in the grout during the test.

Figure 3-4. Brookfield Rheometer and Helipath™ stand used for the viscosity test.

The Helipath™ stand moves the rheometer at a constant velocity of 7/8 inch (22.22 mm) per minute. The adjustable stops are placed so that the rheometer is able to move 1-¾ inches (44.45 mm) in two minutes. The top stop is also adjusted so that when the container is filled with grout, the spindle is immersed ½ inch (12.7 mm) into the grout. Special T-bar spindles (spindle A and B) were used for this test. The rheometer was used with the Rheocalc v2.4 software. The Rheometer was set to spin at 12 rpm, to take readings every 15 seconds, and to run for 30 minutes, so viscosity variation with respect to time could also be studied.

This test has three objectives. The first was to determine the viscosity of several grouts using a Brookfield Rheometer. Second, the viscosity was compared to the efflux time obtained from the flow cone test (Modified ASTM C939-02). This comparison will determine if there is any correlation between the efflux time and the viscosity of a grout, allowing the simple efflux time test to be use if a relationship is determined. Third, viscosities at different depths were evaluated using a Brookfield Helipath™ stand, on which the Rheometer was mounted, which raises and lowers the Rheometer in order to obtain viscosity measurements at different depths. This measurement of viscosity at different depths is important because the viscosity of the grout at the top of the duct may be different from the bottom of the duct due to settlement of grout particles. This will assist the researchers in determining whether void formations from viscosity changes are more likely at lower or higher locations at the duct.

The Helipath™ stand also allows the spindle to cut through fresh material, eliminating the channeling effect that is produced by conventional spindles. It is one of the goals of this test to use the viscosity variation with respect to depth to determine the homogeneity of the grout. It is expected that the more homogeneous a grout mixture is, the less the viscosity will vary with respect to depth. This information is important in PT applications as it provides information on the variation in flow in a duct. A detailed description of the procedures to perform this test is shown in Appendix A, section A.1.

3.3.3. Flow Cone

The flow cone test is a test that determines the efflux time of freshly prepared grouts. The flow cone test was performed in the laboratory following the Tex-437-A: *Test for Flow of Grout Mixtures (Flow Cone Method)* (TxDOT 1999). This test can be performed both in the laboratory and in the field, and the efflux time is determined by measuring the time taken to flow a certain amount of grout through the discharge tube of the flow cone.

Because the grouts used (Class C-1, C-2, and C-3) were identified as being thixotropic grouts, Method 2 of the standard (Tex-437-A) was followed. Figure 3-5 shows the schematic diagram of the flow cone as specified in the Tex-437-A standard specifications. According to this method, the cone was filled to the top with freshly prepared grout and the time required for 2.11 pints (1000 ml) of grout to flow from the cone was reported as the efflux time. The required efflux time from the current TxDOT standard for thixotropic grouts to be used in post-tensioning based on Method 2 of the standard is:

- 9 to 20 seconds immediately after mixing and
- 30 seconds maximum with 30 minutes standing time after initial mixing and remixed for 30 seconds before testing.

The flow cone test was performed for all grouts with three different w/p, three different mixture volumes, and two different mixers.

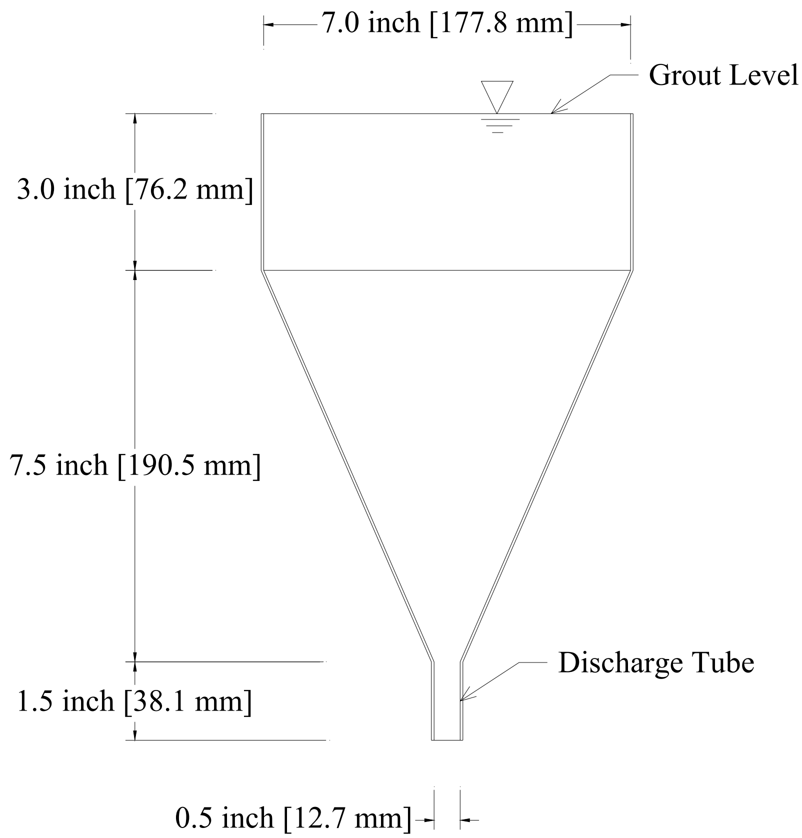


Figure 3-5. Schematic diagram of flow cone as per Tex-437-A specification.

3.3.4. Density

The grout's wet density was measured following American Petroleum Institute's RP 13B-1, to ensure the quality of freshly mixed grouts. One test per grout mixture was performed for all grout mixtures with varying w/p, mixer type, and mixture volume. A discussion of the results of this test is presented later.

To use the Baroid mud balance test as a quality control device, tests have been performed to predict the grout's wet density using the mixture's w/p and powder's dry density. Since the grout's dry density varies from batch to batch it was decided to measure powder's representative dry density in the field using Baroid mud balance. This dry density is not a measure of the grout's specific gravity. Instead it is measured in the field to predict the grout's wet density after mixing. The procedure to measure dry density of grout is described in the Appendix A, section A.2.

The dry density values along with the corresponding mixture's w/p and observed wet density have been used to predict the wet density of the resulting grout mixture. A relationship between the observed and predicted wet density of grout has been formulated. A discussion on the wet density model is present in Section 5.

3.3.5. Compressive Strength

The compressive strength test was performed on all grouts following Tex-442-A: *Determining Compressive Strength of Grouts* (TxDOT 2006), which is identical to ASTM C942-99: *Standard Test Method for Compressive Strength of Grouts for Preplaced-Aggregate Concrete in the Laboratory* (ASTM C942). The compressive strength of three 2-inch (51 mm) grout cubes were determined using this test method at 1, 3, 7, 28, and 56 test ages. Stainless steel and brass cube mold conforming to ASTM C109-05: *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars*

(Using 2-in. or [50-mm] Cube Specimens), were used to cast the cubes. For each mixture, the compressive strength was expressed as the average of three cube compressive strengths at each of the selected test ages.

3.3.6. Volume Change

ASTM C1090-01 (2005) *Standard Test Method for Measuring Changes in Height of Cylindrical Specimens of Hydraulic-Cement Grout* (ASTM C1090) was followed to evaluate the expansion/shrinkage of all grouts. One test per grout mixture was performed for all grouts with varying w/p, mixer type, and mixture volume. Expansion/shrinkage measurements were taken after 1, 3, 7, 14, and 28 days as specified in ASTM C1090. Figure 3-6 shows the micrometer bridge set used to measure the change in height of cylindrical specimen.

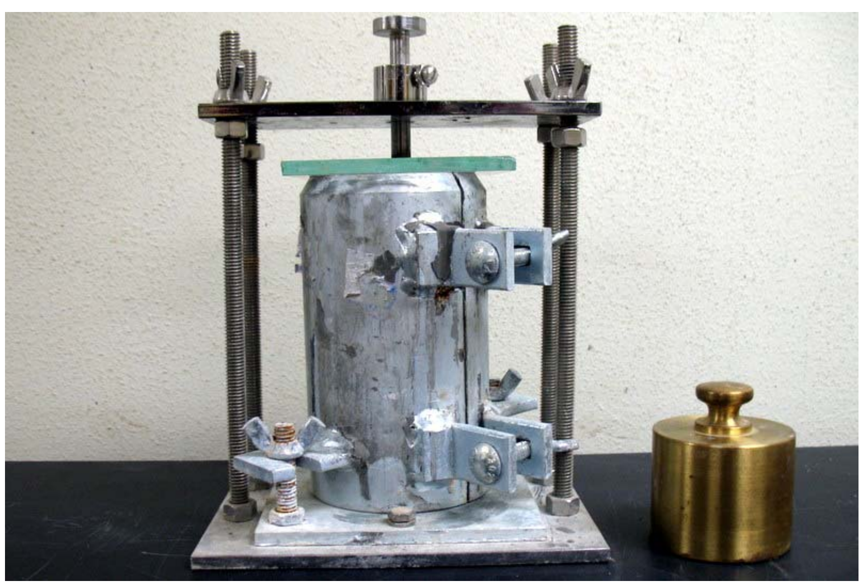


Figure 3-6. Volume change apparatus conforming to ASTM C1090 used to measure change in height of cylindrical specimens.

3.3.7. Chloride Diffusion

ASTM C1556-03 test standard was followed to determine the apparent chloride diffusion coefficient of the PT grouts corresponding to their manufacturers' recommended w/p., 0.50 ft^3 (0.0142 m^3) mixture volumes, and using both the M1 and M2 mixers. Cylinders of dimension 3 inch by 6 inch (51 mm by 102 mm) were cast for all combinations of mixtures and cured for 28 days in a 100% humidity environment.

Figure 3-7 gives a detailed description of the cylindrical sample and sections tested. The test specimens were prepared by cutting sections parallel to the ends. The top 2.95 inch (75 mm) of the cylinder sample was used as test specimen, the next 0.79 inch (20 mm) thick slice was used to determine the initial chloride content, and the remaining sample was discarded. The test specimens were then coated with epoxy on all sides except for the finished (or cut) surface and exposed to the exposure solution. After 35 days of ponding, powdered samples were collected following the profile grinding procedure in ASTM C1556 (2003).

For all samples a total of five depths were ground and tested. These depths were determined from the recommended depth interval table in ASTM C1556 (2003). The five chosen depth intervals were top three depths and depth 6 and 8 respectively and are shown in Table 3-7. The chloride content was determined for each sample and then, using the initial chloride content, the apparent chloride diffusion coefficient (D_a) was determined using Equation 2.5. Note that this is one-dimensional flow and only provides a relative measure of chloride resistance for PT ducts.

Table 3-7. Chosen depth intervals in inches (mm) based on ASTM C1556 standard.

Grout type	Class A		Class C-1		Class C-2		Class C-3	
	inch	**mm**	**inch**	**mm**	**inch**	**mm**	**inch**	**mm**
Depth 1	0-0.04	0-1	0-0.04	0-1	0-0.04	0-1	0-0.04	0-1
Depth 2	0.04-0.12	1-3	0.04-0.08	1-2	0.04-0.08	1-2	0.04-0.08	1-2
Depth 3	0.12-0.20	3-5	0.08-0.12	2-3	0.08-0.12	2-3	0.08-0.12	2-3
Depth 6	0.43-0.55	11-14	0.24-0.31	6-8	0.20-0.24	5-6	0.20-0.24	5-6
Depth 8	0.71-0.87	18-22	0.39-0.47	10-12	0.31-0.39	8-10	0.31-0.39	8-10

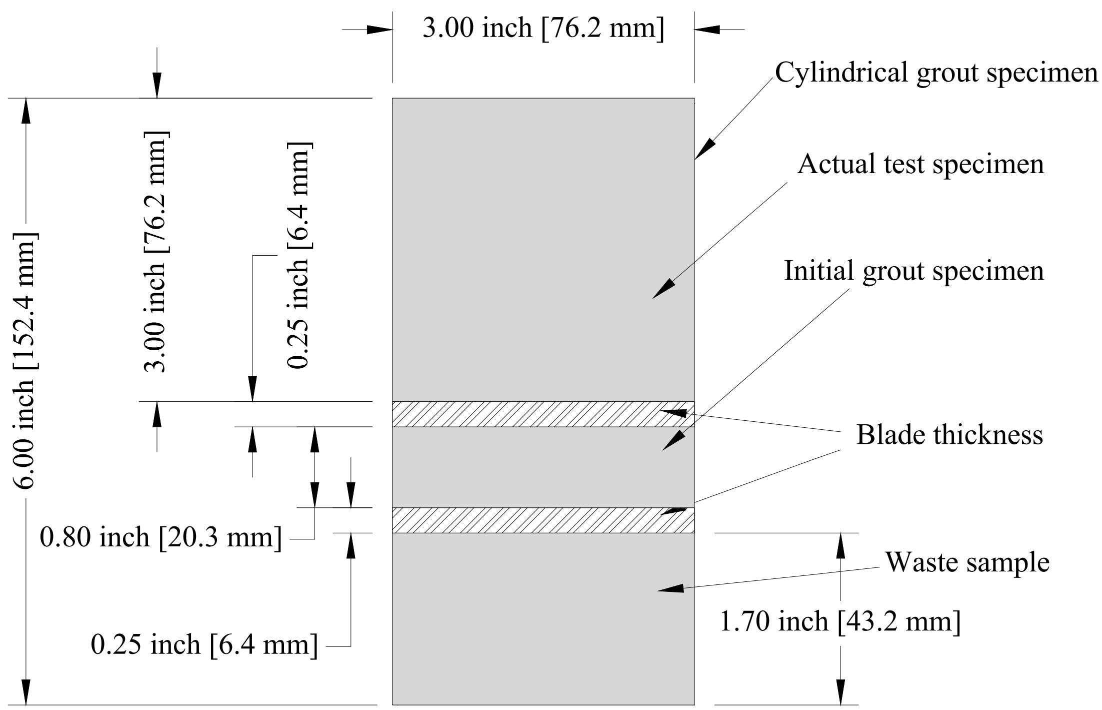


Figure 3-7. Cylindrical specimen for chloride diffusion.

3.3.8. pH

The pH of the grout's pore solution was measured by extracting the pore solution of the grout cylinders after 28 days of curing. Three cylindrical samples, 2 inch by 4 inch (51 mm x 102 mm), were cast. Figure 3-8 shows the pore fluid expression device used to extract the pore solution. Several steps were followed in extracting the pore solution of cylinders. A detailed test procedure is shown in Appendix A, Section A.3.

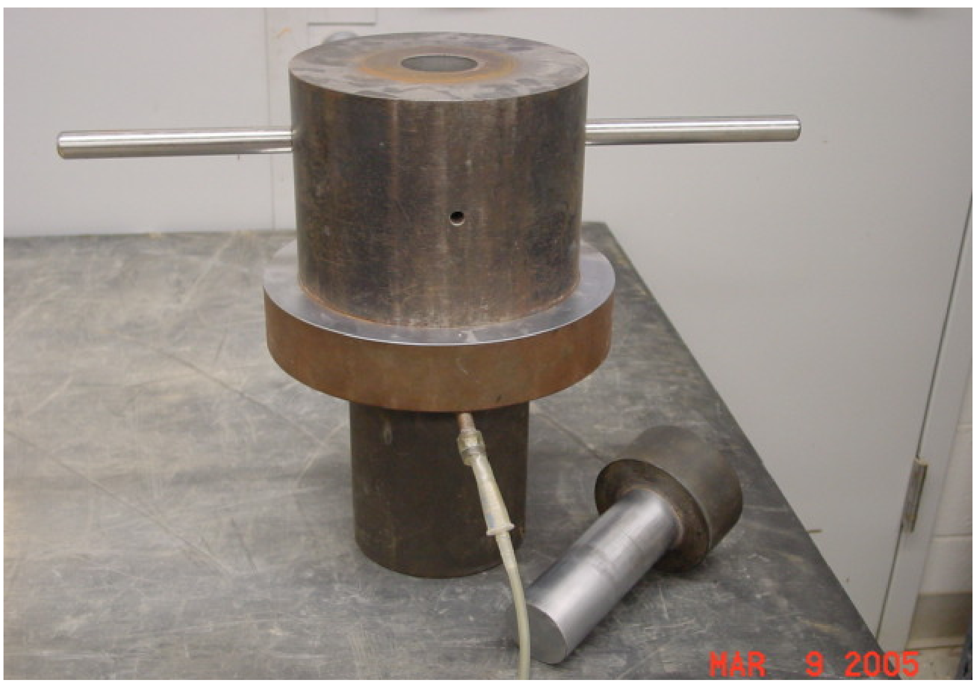


Figure 3-8. Pore fluid expression device to measure pH of pore solution.

3.4. Fillability Meter

The fillability meter was designed with the aim of evaluating various grouts in terms of their ability to fill small voids in PT ducts. Freshly prepared grout was placed under pressure and the minimum and maximum filter sizes at which there is no flow and good flow was determined. The fillability meter vessel was fabricated using PVC Schedule 40 and Schedule 80 pressure fittings. The meter consists of a pressurized vessel with capacity of 0.07 ft^3 (2000 ml), a pressure hose connection through which pressure can be applied, and a set of filters.

Figure 3-9 shows a cross-section of the fillability meter. After the fillability meter was fabricated, pilot tests were performed to test for leaks. The meter was tested at 60 psi (0.42 MPa) pressure. Fillability tests were then performed to study the fillability of various grouts. Ten different 2 inch (51 mm) diameter pore size filters were used and the sizes of the pore opening were as follows:

- 0.0055 inch (140 μm)
- 0.007 inch (178 μm)
- 0.009 inch (229 μm)
- 0.015 inch (381 μm)
- 0.021 inch (533 μm)
- 0.03 inch (762 μm)
- 0.034 inch (864 μm)
- 0.054 inch (1372 μm)
- 0.065 inch (1651 μm)
- 0.08 inch (2032 μm)

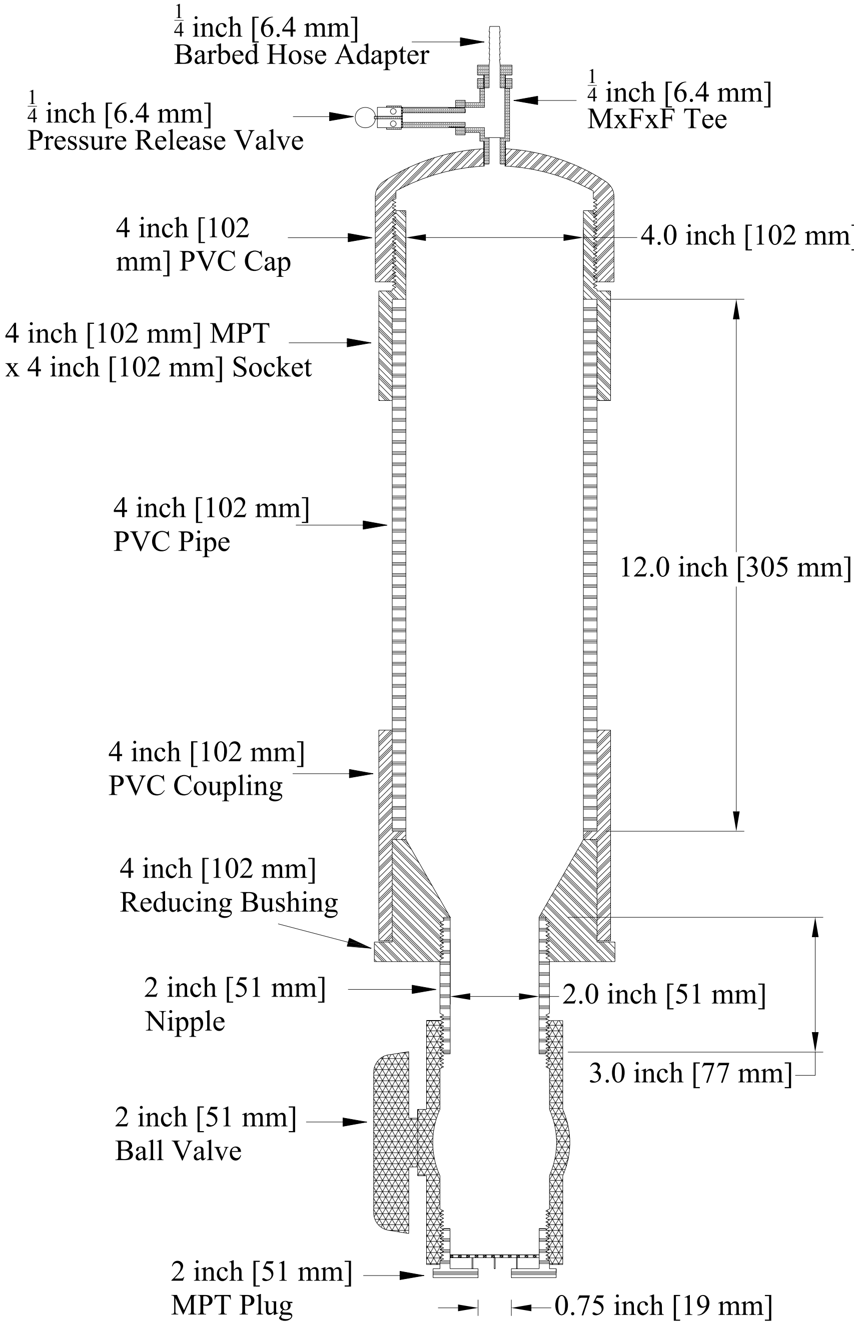
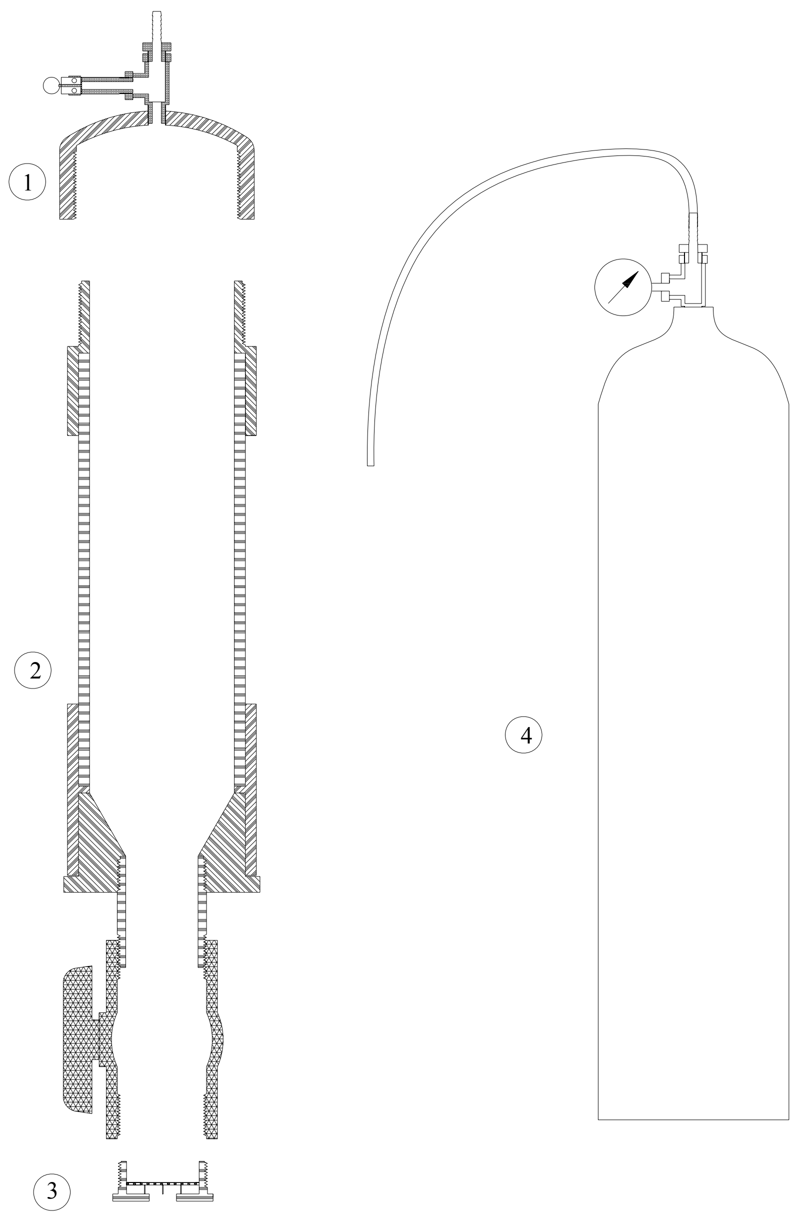


Figure 3-9. Detailed sketch of fillability meter.



Fillability meter parts:
1. Top cap with attached barbed hose adapter for connecting with air supply
2. Grout vessel with 2 inch (51 mm) valve at hte bottom to control the flow of grout through filter.
3. Male pipe thread plug with filter.
4. Pressurized air supply cylinder.

Figure 3-10. Fillability meter parts for use in fillability test.

The fillability test was performed on the Class C grouts. The steps to perform the test were as follows:

1. Mount the grout vessel (2) shown in Figure 3-10 to the table near the compressed air supply (4).
2. Close the grout outlet valve at the bottom of grout vessel (2).
3. Place a 2-inch diameter stainless steel wire cloth woven filter in the 2-inch Male Pipe Thread (MPT) Plug (3) and affix it to the ball valve of the grout vessel.
4. Prepare a grout mixture following manufacturer's recommended w/p to produce at least 0.25 ft^3 (0.0071 m^3) of grout. Immediately after mixing, perform a flow cone test following Tex-437-A standard to measure the efflux time of the resulting grout mixture.
5. Measure 4.23 pints (2000 ml) of freshly prepared grout in a scoop, pour it into the grout vessel (2) and close the top 4-inch (102 mm) cap with the threaded connection (1). Attach pressure hose to the ¼-inch (6.3 mm) barbed adapter and apply pressure equal to 20 psi (0.14 MPa).
6. Maintain the pressure at 20 psi (0.14 MPa) and open the bottom 2-inch (51 mm) valve and collect the grout flowing through the filter in a 2.12 pints (1 L) graduated cylinder with a resolution of 0.02 pints (10 ml). Release the pressure if no grout or all grout flows through the filter. Measure the volume of grout collected in the graduated cylinder and document this volume.

After the fillability test is performed, a plot of volume passed versus the filter size can provide an indication of the filling ability of a particular grout. To express the fillability in terms of a number, the fillability index has been defined as the average percent volume retained on the chosen filters. This can be defined in the same way as the fineness modulus of fine aggregates. The fillability index (FI) is expressed as:

$$\mathrm{FI} = \frac{\sum_{i}^{n} \%\,\mathrm{VR}_i}{100} \tag{3.2}$$

where n is the number of different sized filters, and $\%\mathrm{VR}_i$ is the percentage of total volume retained on the ith filter.

Table 3-8 shows a typical observation table used to record the volume of grout passed through various filters. Columns 3 and 4 show the filter sizes. Column 5 is used to record the volume of grout passed through the specific filter. Once the volume of grout passed through all filters has been recorded then the percent volume passed from the total volume of 4.23 pints (2000 ml) can be calculated. The percent volume retained (VRi) can be determined by subtracting the percent volume passed from 100. The fillability index can then be calculated using Equation 3.2.

Table 3-8. Example table showing observations for the fillability index.

Grout **(1)**	**Filter No.** **(2)**	**Filter Size (inch)** **(3)**	**Filter Size (μm)** **(4)**	**Volume passed, pints (ml)** **(5)**	**Percent volume passed** **(6)**	**Percent volume retained (VR_i)** **(7)**
Grout class	#10	0.08	2032	4.23 (2000)	100	0
	#12	0.065	1651	4.23 (2000)	100	0
	#16	0.054	1372	4.23 (2000)	100	0
	#20	0.034	864	4.23 (2000)	100	0
	#24	0.03	762	4.23 (2000)	100	0
	#30	0.021	533	2.94 (1390)	69.5	30.5
	#40	0.015	381	0.82 (390)	19.5	80.5
	#60	0.009	229	0.13 (60)	3	97
	#80	0.007	178	0.02 (10)	0.5	99.5
	#100	0.0055	140	0 (0)	0	100
					Fillability Index, FI =	**4.1**

4. MATERIAL CHARACTERIZATION

This section contains the material characteristics including the powder's scanning electron microscopy (SEM) analysis, the fines' particle size distribution, and the sieve analysis for grout powders.

4.1. Scanning Electron Microscopy

To provide general information on the constituents of these pre-packaged grouts, a scanning electron microscope (SEM) was used to obtain micrographs of the grouts. A JOEL JSM-6400 SEM was used and micrographs were obtained at magnifications of 1000x. Figure 4-1, 4-2, 4-3 and 4-4 show SEM micrographs of the ASTM Type I cement and the grouts C-1, C-2, and C-3 respectively. Results indicate that grouts have particles similar to Type I or III cement and need magnifying photos to determine if silica fume is present. The SEM micrographs of C3 grout (Figure 4-4) show that spherical fly ash particles are likely to be present.

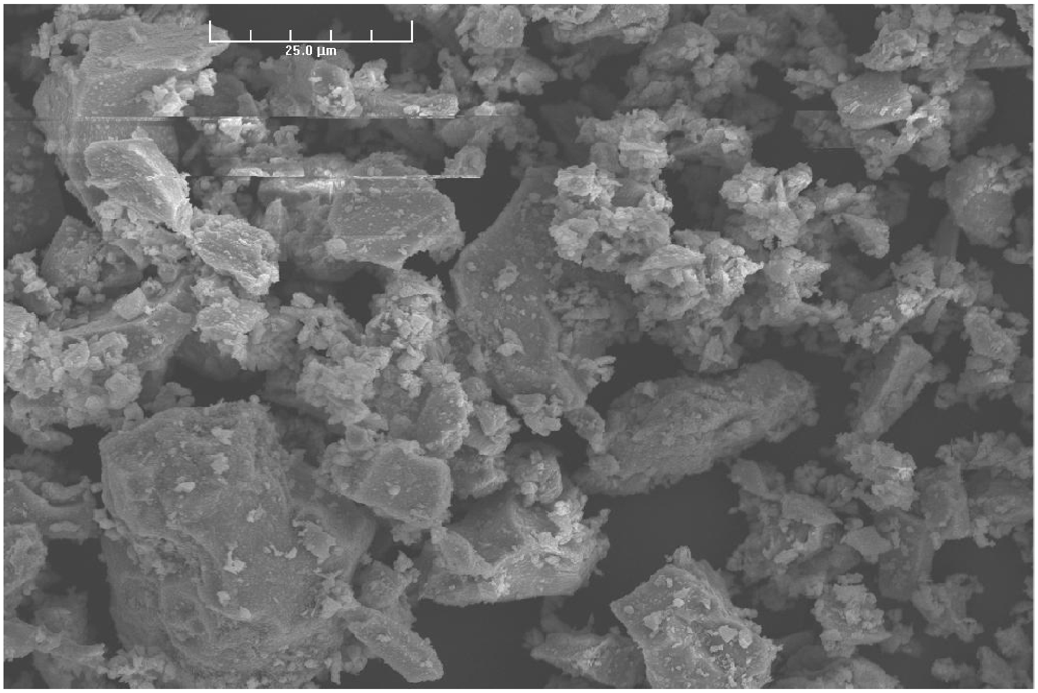


Figure 4-1. SEM micrograph of ASTM Type I cement particles (1000x).

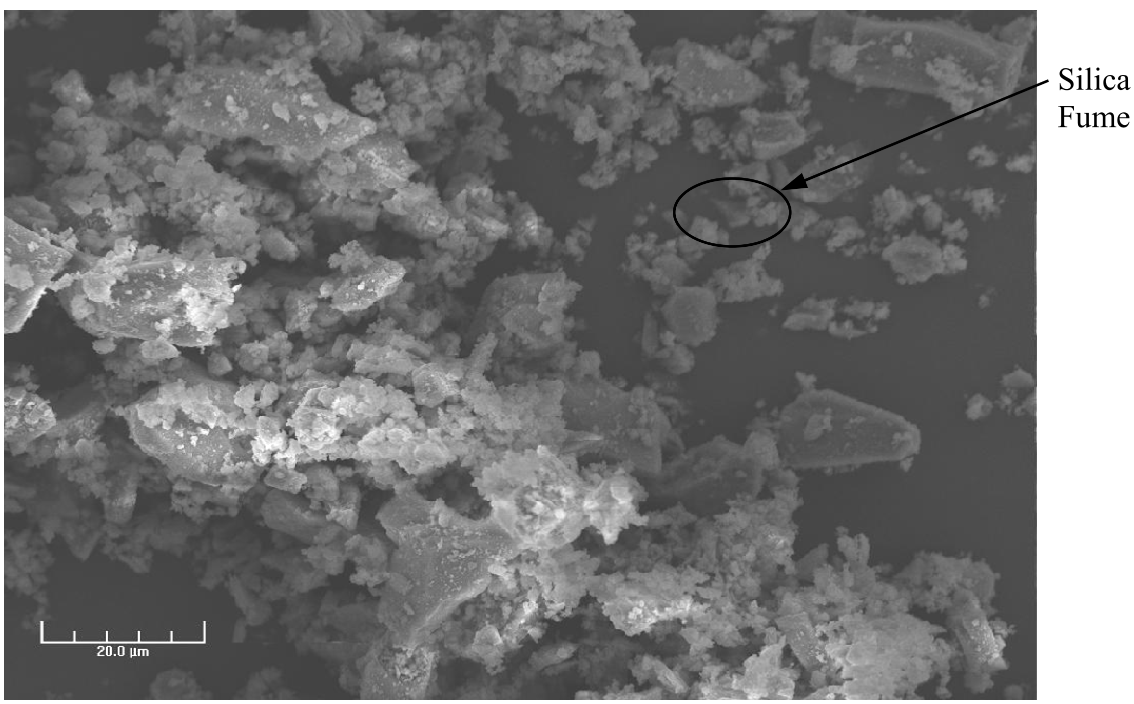


Figure 4-2. SEM micrograph of Class C-1 grout particles (1000x).

Figure 4-2 shows the SEM micrograph of Class C-1 grout. Most particles are smaller than Type I cement particle (shown in Figure 4-1). This indicates the possible presence of fine supplementary cementitious particles. Because fly ash particles are spherical in shape and are generally of the order of 1 to 10 μm. The small particles may be silica fume.

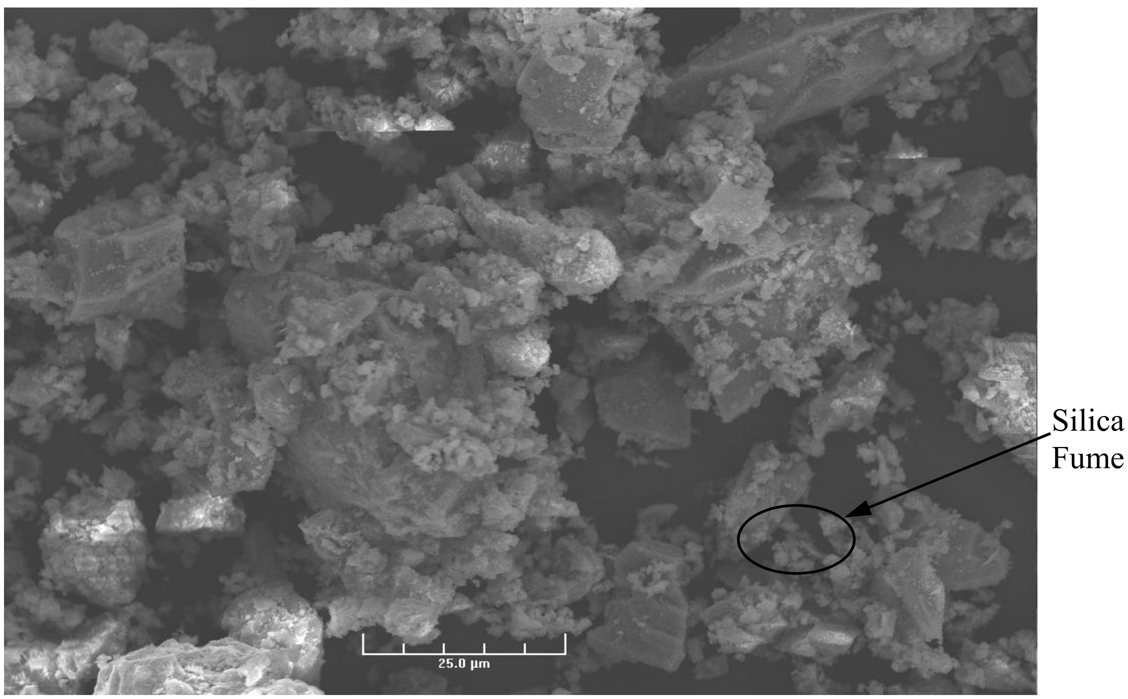


Figure 4-3. SEM micrograph of Class C-2 grout particles (1000x).

Figure 4-3 shows the SEM micrograph of Class C-2 grout. The maximum particle size seem to be similar to or smaller than the Type I cement (Figure 4-1 above), indicating the presence of Type III cement. Also many small size particles (< 1 μm) are present which indicate that silica fume may be in the mixture.

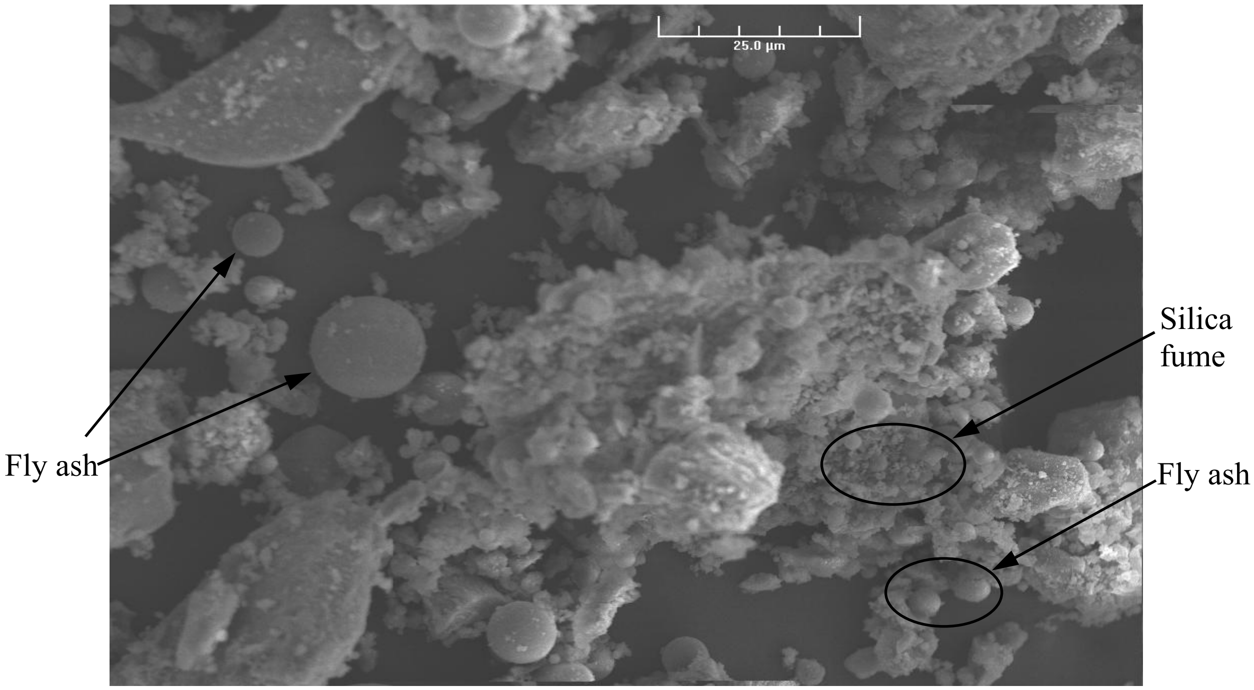


Figure 4-4. SEM micrograph of Class C-3 grout particles (1000x).

Figure 4-4 shows the SEM micrograph of Class C-3 grout. The maximum cement particle sizes seem to be smaller than the Type I cement (Figure 4-1) indicating this grout may contain Type III cement or silica fume. Spherical particles between 5 to 15 µm are present indicating the presence of fly ash.

4.2. Particle Size Distribution

A particle size distribution analysis was performed on all grouts using a laser particle size analyzer. A Horiba LA900 laser particle size analyzer was used to obtain the particle size distribution of the fines, smaller than 0.004 inch (100µm). Ethanol (CH_3CH_2OH) was used as solvent to disperse the grout particles.

Figure 4-5 shows the particle size distribution for the fines of the grouts. The graph indicates that Class C-1 grout particles are finer than the particles in the other grouts. The particles in the Class C-3 grout were larger than all other grouts including the Class A grout.

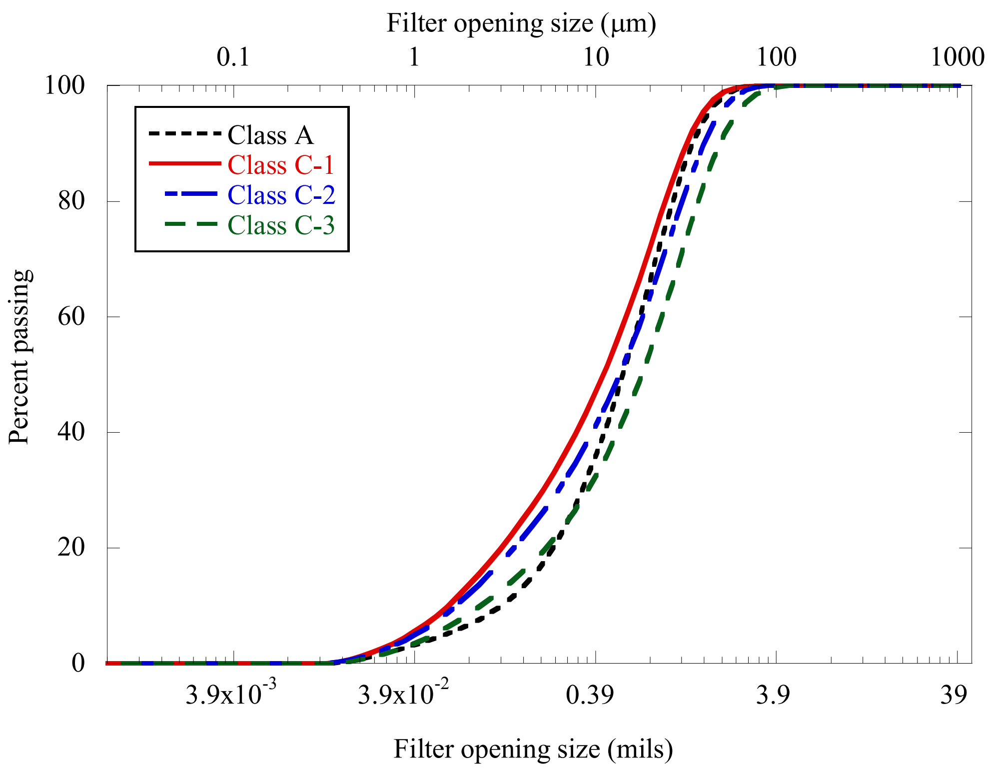


Figure 4-5. Particle size distribution of following four grouts for fines less than 0.004 inch (100 μm).

While performing the fillability test for Class C-3 grout, it was noted that the filters became clogged by larger sand particles. Figure 4-6 shows the sand particles collected from the clogged 0.015 inch (381μm) filter. A sieve analysis was performed on the Class

C-3 grout to determine the percentage of particles larger than 0.004 inch (100 μm). Sieves of sizes 0.017, 0.010, 0.007, 0.004, and 0.002 inch (425, 300, 250, 180, 90, and 50 μm) and conforming to ASTM C184: *Standard Test Method for Fineness of Hydraulic Cement by the 150-μm and 75-μm Sieve* (ASTM C184), were used to perform the sieve analysis. A 1.1 lb (0.5 kg) sample of dry Class C-3 grout was weighed to perform the sieve analysis and the sieve shaker was run for 5 minutes. Table 4-1 shows the percent passing and percent retained weights on each sieve.

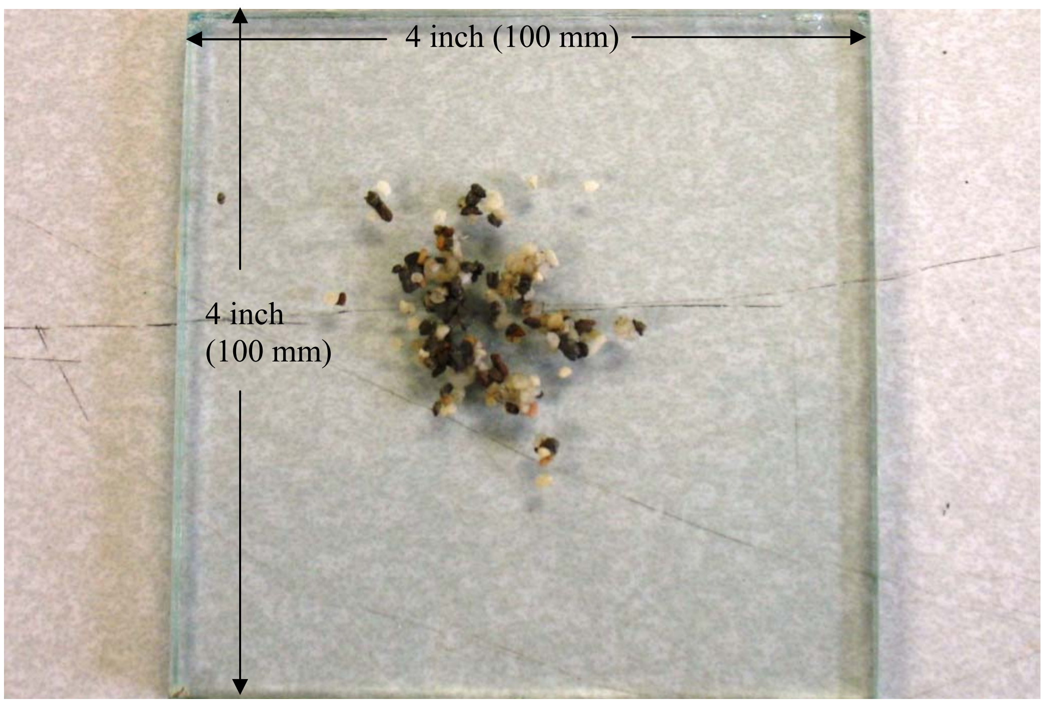


Figure 4-6. Sand particles in Class C-3 grout.

Table 4-1. Sieve analysis of Class C-3 grout.

Sieve size		Weight retained						Percent Retained	Cumulative Percent Retained	Percent Passing
		Empty		With Grout		Grout Only				
(inch)	(μm)	(lb)	(gm)	(lb)	(gm)	(lb)	(gm)			
0.017	425	1.28	580.5	1.28	583	0.01	2.5	0.5	0.5	99.5
0.012	300	1.22	554.5	1.23	557.5	0.01	3	0.6	1.1	98.9
0.010	250	1.16	526	1.18	538.5	0.03	12.5	2.5	3.6	96.4
0.007	180	1.14	519	1.17	534	0.03	15	3	6.61	93.39
0.004	90	1.05	476	1.48	671	0.43	195	39.04	45.65	54.35
0.002	50	0.64	289.5	1.23	561	0.60	271.5	54.35	100	0

Figure 4-7 shows the particle size distribution obtained from the sieve analysis. It is observed that more than 1 percent of the C-3 grout particles were larger than 0.012 inch (300 μm). These larger size particles could block passage of the grout through small voids and hinder the flow of grout through smaller voids. Only Class C-3 grout clogged the filters due to the large size particles (Figure 4-6), hence the particle size distribution analysis was performed on Class C-3 grout only.

It should be noted that the PT grouts must not contain fine aggregates as these aggregates could clog the grout through small openings and may result in formation of more voids which lead to durability issues. Therefore, it is recommended that the maximum size fine aggregates allowed in the PT grout should be reduced to No. 100 Sieve (150 μm) instead of No. 50 Sieve (300 μm).

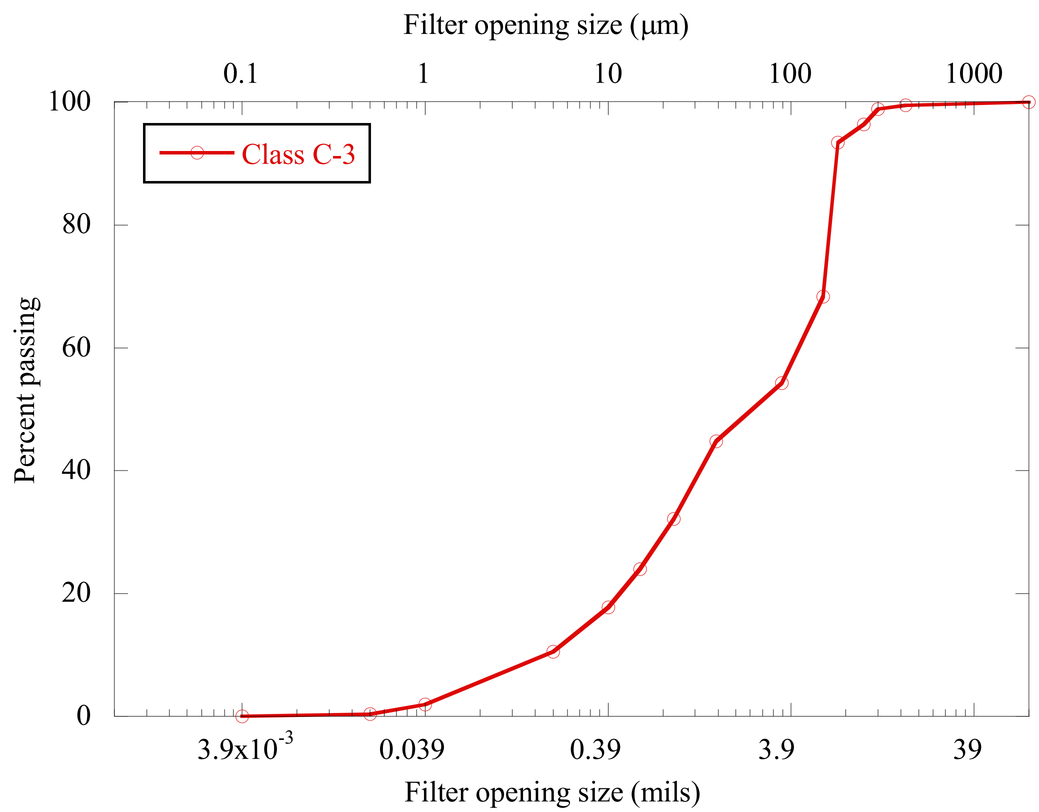


Figure 4-7. Particle size distribution of Class C-3 grout by combining sieve analysis data and fines data analyzed through laser particle size analyzer.

4.3. Initial Setting Time

The grout's initial setting time is also an important material characteristic because it indicates the time interval during which the grout will be fluid and is good to fill PT ducts. According to the current TxDOT grout requirements for the PT applications, DMS 4670: *Grouts for post-tensioning*, the grout should have an initial setting time between 3 hours to 12 hours. Setting time was evaluated for all grouts and the different mixers. Results will be shown in Section 5.

5. RESULTS AND DISCUSSION

This section contains the test results obtained from the research. The tests were performed according to the test matrix shown in the previous section.

5.1. Fresh Characteristics

The results on how mixer-type, mixture volume, and w/p influences the fresh characteristics of grout are presented in this section.

5.1.1. Wick-Induced Bleed

The wick-induced bleed test was performed for all grouts following Tex-441-A. Three tests for each grout mixture were performed and an average of three bleed cylinders was expressed as the overall percent bleed.

Figures 5-1 and 5-2 show the grout bleed results of the grouts for the three w/p values and both mixers. The research indicates that grouts C-1, C-2, and C-3 did not bleed. The Class A grout (w/p = 0.44) exhibited an average bleed of approximately 2 percent. The Class C grouts (C-1, C-2, and C-3) meet the maximum permissible bleed recommended by the PTI 2003 and the current TxDOT specifications.

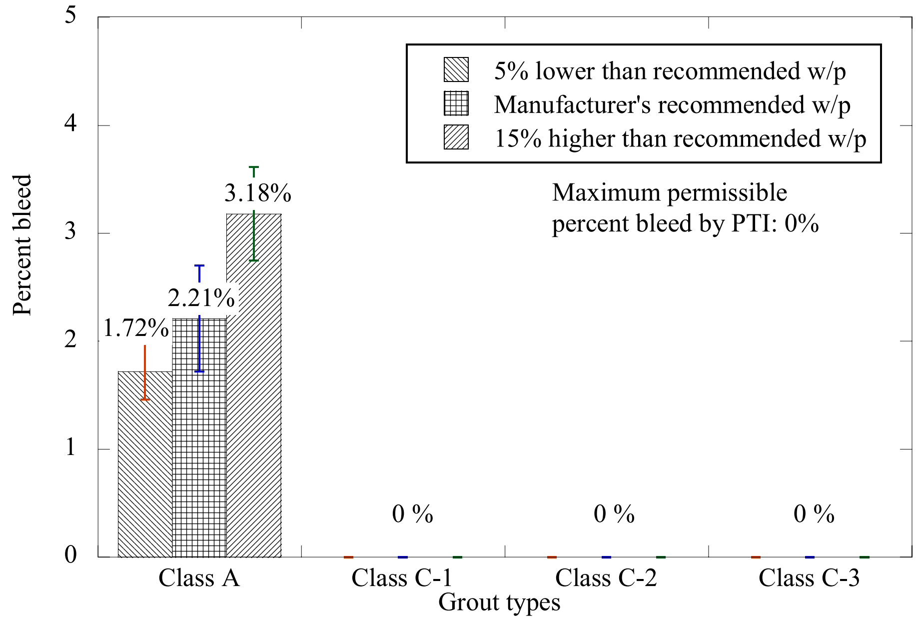


Figure 5-1. Wick-induced bleed results for grouts based on different w/p using M1 mixer.

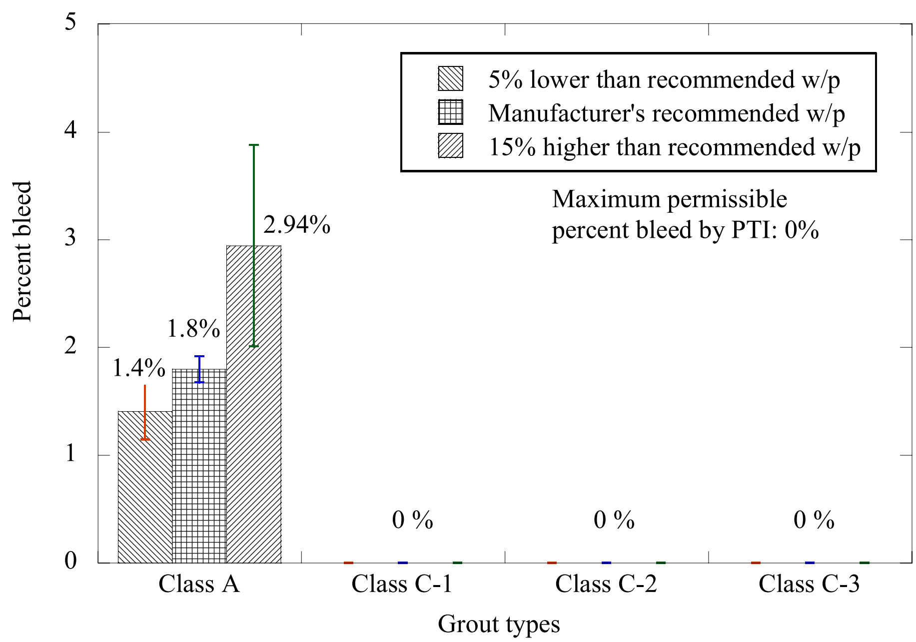


Figure 5-2. Wick-induced bleed results for grouts based on different w/p using M2 mixer.

The variation of class A grout bleed water with respect to the w/p, mixture volume, and mixer type is shown in the Figure 5-3. Here, the L, R, and H represent the corresponding 5% lower (0.42), recommended (0.44), and 15% higher (0.51) w/p's respectively. The values 0.25, 0.50 and 0.75 represent the size of mixture volume as 0.25, 0.50, and 0.75ft^3 (0.0071, 0.0142, and 0.0213 m^3). Because a set of three bleed cylinders were tested for each mixture, the lines on the top of bars represent the standard deviation in the bleed results obtained from three cylinders.

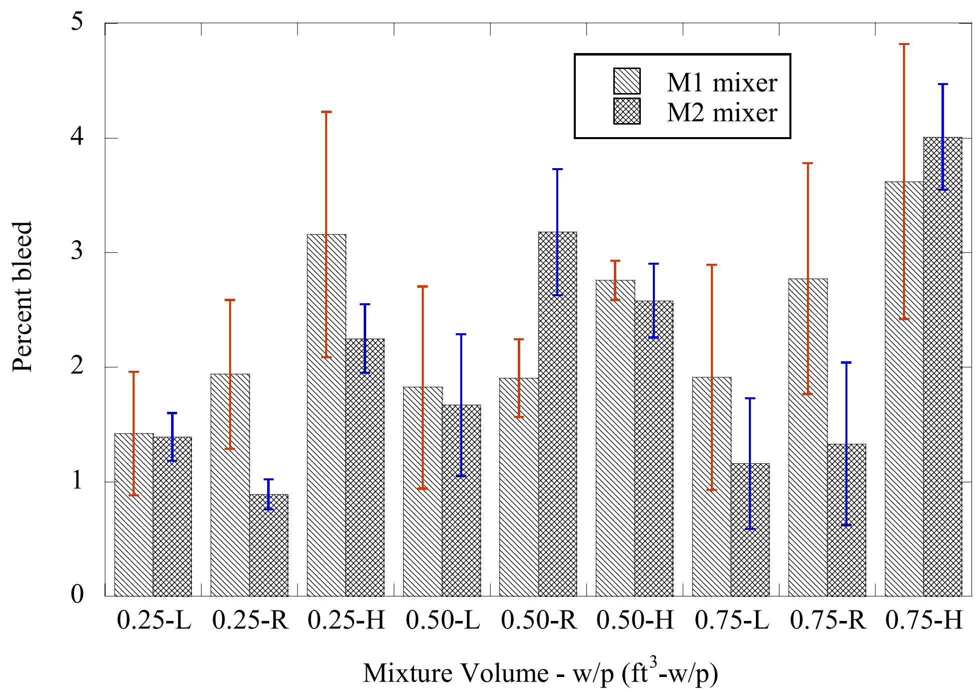


Figure 5-3. Wick-induced bleed results for Class A grout.

A randomized single factor analysis of variance (ANOVA) test was performed to determine whether the change in mixture volume reduces the bleeding of grout. For the sake of simplicity, it was assumed that the percent bleed varies linearly with the mixture volume. By assuming a linear statistical model, the observations can be described as shown below:

$$Y_{ij} = \mu + \tau_i + \varepsilon_{ij} \begin{cases} i = 1,2,\ldots,a \\ j = 1,2,\ldots,n \end{cases} \tag{5.1}$$

where Y_{ij} is a random variable denoting the (*ij*)th observation, μ is a parameter common to all treatments referred to as the overall mean, τ_i is a parameter associated with the *i*th treatment called the *i*th treatment effect, and ε_{ij} is the random error component that is assumed to be normally distributed with a zero mean and σ^2 variance. The null hypothesis (H_0) and alternate hypothesis (H_1) formulated for this purpose are defined as shown below:

$$\begin{aligned} H_0 &= \tau_1 = \tau_2 = \tau_3 = 0 \\ H_1 &= \tau_i \neq 0 \,\text{for at least one}\, i \end{aligned} \tag{5.2}$$

Assuming a 5% level of significance, the single factor ANOVA test results are presented in the Table 5-1. From the analysis results, it can be concluded that sufficient evidence is not available to reject the null hypothesis (H_0). Mixture volume does not significantly affect the percent bleed of the Class A grout.

Table 5-1. Single factor ANOVA for wick-induced bleed result of Class A grout assessing effect of mixture volume on the bleed.

Source of Variation	Sum of Squares	Degrees of freedom	Mean Sum of Squares	F statistic	F critica	*p*-value
Mixture volume	0.0017	2	0.0009	0.0017	5.1433	0.9983
Within (SSe)	3.1155	6	0.5193			
Total	3.1172	8				

Once it was identified that the mixture volume does not significantly affect the grout bleed, the effect of mixer type and w/p on the bleed rate were evaluated by assuming a two-factorial linear model as follows:

$$Y_{ijk} = \mu + \tau_i + \alpha_j + (\tau\alpha)_{ij} + \varepsilon_{ijk} \begin{cases} i = 1,2 \\ j = 1,2,3 \\ k = 1,\ldots,9 \end{cases} \tag{5.3}$$

The hypotheses for both treatment variables (mixer type and w/p) and their interaction are shown as:

$$\begin{aligned} &1.\ H_0 = \tau_1 = \tau_2 = 0 \\ &\quad H_1 = \tau_i \neq 0 \text{ for at least one } i \\ &2.\ H_0 = \alpha_1 = \alpha_2 = \alpha_3 = 0 \\ &\quad H_1 = \alpha_j \neq 0 \text{ for at least one } j \\ &3.\ H_0 = (\tau\alpha)_1 = (\tau\alpha)_2 = \ldots = (\tau\alpha)_k = 0 \\ &\quad H_1 = (\tau\alpha)_k \neq 0 \text{ for at least one } k \end{aligned} \tag{5.4}$$

Table 5-2 summarizes the results obtained from the two-factorial statistical analysis for the hypotheses discussed above. At 5% level of significance it is concluded that the mixer type has no significant effect on the grout bleed whereas the w/p significantly affects the grout bleed. Because Class C grouts (C-1, C-2, and C-3) did not exhibit any bleed, no analysis is needed to evaluate the effect of either mixture volume, w/p, or the mixer type on the bleed.

Table 5-2. Two-factorial ANOVA for wick-induced bleed result of Class A grout assessing effect of mixer type and w/p on the bleed.

Source of Variation	Sum of Squares	Degrees of freedom	Mean Sum of Squares	F statistic	F critical	*p*-value
Mixer Type	1	1	1	1.130	4.043	0.293
w/p	22	2	11	24.373	3.191	0.000
Interaction	0	2	0	0.261	3.191	0.772
Within (SSe)	22	48	0			
Total	44	53				

5.1.2. Viscosity

The time-dependent viscous behavior of the grouts were studied. For each grout and mixture type viscosity measurements were taken for a minimum of 30 minutes. Figure 5-4 and Figure 5-5 show the viscosity as a function of time for the Class A, C-2, and C-3 grouts while mixing with their recommended w/p using the M1 and M2 mixers. The viscosity of the grouts increased with time as would be expected due to hydration.

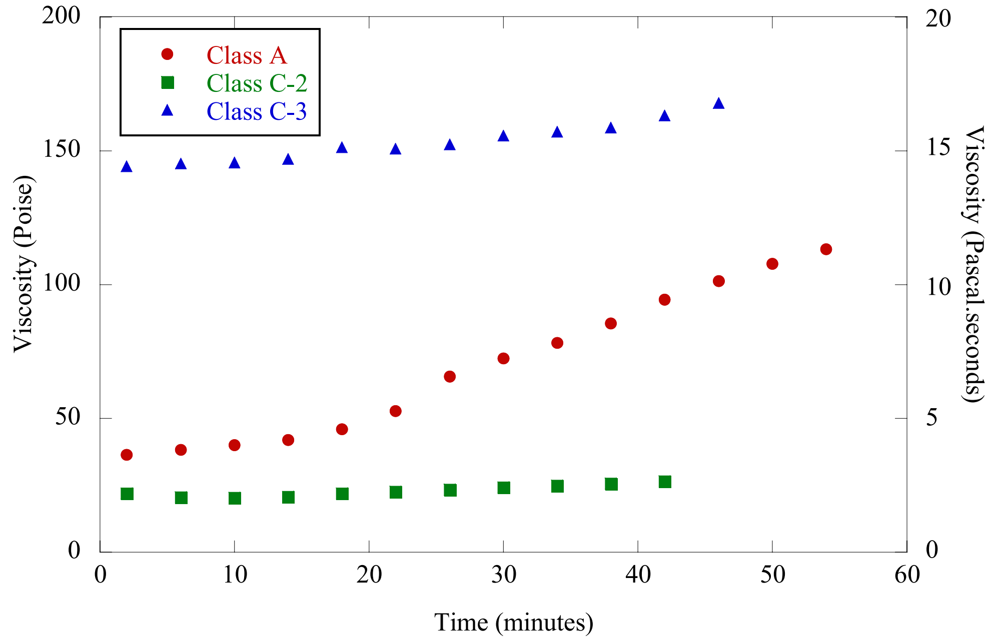


Figure 5-4. Time dependent viscosity of Class A, C-2, and C-3 grouts mixed with M1 mixer.

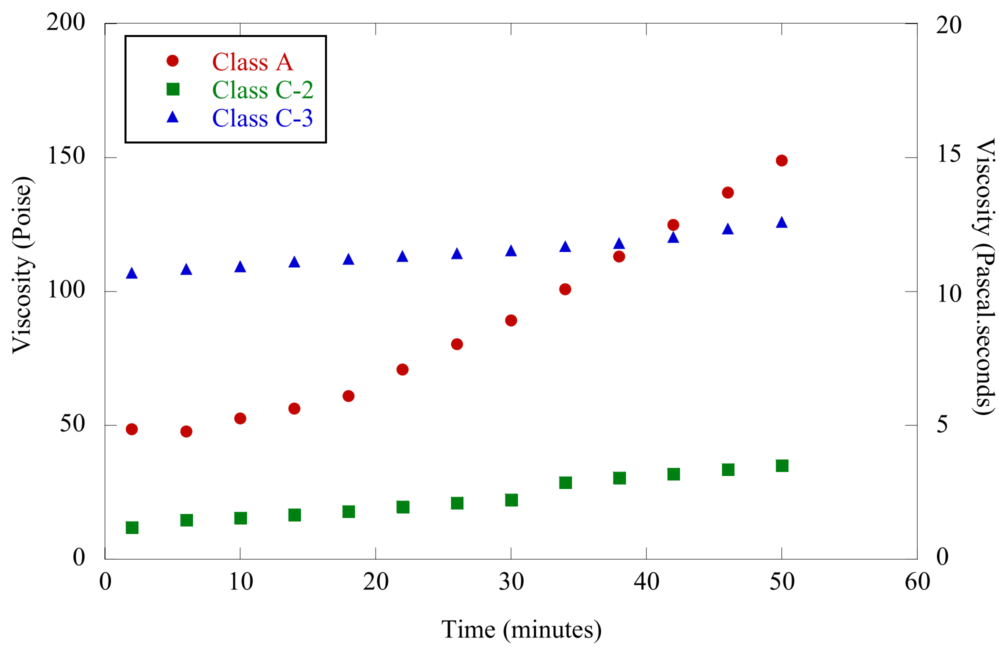


Figure 5-5. Time dependent viscosity of Class A, C-2, and C-3 grouts mixed with M2 mixer.

The viscosity measurements show that grout C-2 exhibits a much lower viscosity when compared to grout C-3 at the corresponding manufacturer's recommended w/p. It was also observed that, for Class C grouts (C-2 and C-3) the mixture prepared with the M2 mixer resulted in relatively low viscous mixture as compared to the mixture prepared with M1 mixer. Class A grout showed a sharp increase in viscosity with time. This could be due to the initiation of hydration of the Class A grout. Based on the results obtained from the viscosity tests, it can be concluded that the Class C-2 grout exhibits lower viscosity values than the Class C-3 grout.

To evaluate the effect of mixer type on the viscosity of grouts, a *t*-test was performed. In the null hypothesis, it is assumed that the mixer type does not produce any significant difference in viscosity. Hence, the null and alternate hypotheses are defined as follows:

$$\begin{aligned} H_0 &: \mu_1 - \mu_2 = 0 \\ H_1 &: \mu_1 - \mu_2 \neq 0 \end{aligned} \tag{5.5}$$

where μ1 and μ2 are the average viscosities of grouts corresponding to M1 and M2 mixers, respectively. Table 5-3 shows the results of the t-test performed to compare the effect of mixer on the viscosity of grouts. Assuming a 0.05 level of significance, it is concluded that mixer type significantly affects viscosity of the Class C-3 grout. M2 mixer results in lower viscosity values. It is also concluded that sufficient evidence is not available to reject the null hypotheses for Class A and C-2 grouts. Hence, mixer type does not significantly affect the viscosity of Class A and C-2 grouts. Although the viscosities of all grouts are not significantly affected by the mixer type, the M2 mixer could provide better mixing.

Table 5-3. Summary statistics for the t-test to compare effect of mixer on the viscosity of grout.

Source of Variation	Grout	t_0	t critical	*p*-value
Mixer Type	A	1.802	2.379	0.087
	C2	0.003	2.379	0.998
	C3	12.499	2.379	0.000

5.1.3. Fluidity

The fluidity of the grouts can be assessed by evaluating the efflux time for each grout mixture. One test was performed for each mix as specified by the Tex-437-A specifications. The currently accepted values for efflux time according to the Tex-437-A standard are:

- Between 9 and 20 seconds for efflux time measured immediately after mixing,
- Less than 30 seconds for efflux time measured 30 minutes after the mixing

The results obtained from the testing have been analyzed and Figures 5-6, 5-7, 5-8, and 5-9 depict the variation of efflux time as the mixture volume changes. The efflux time measurements shown in these graphs are from mixes with w/p values equal to their manufacturers' recommended w/p and using M1 and M2 mixers for mixing.

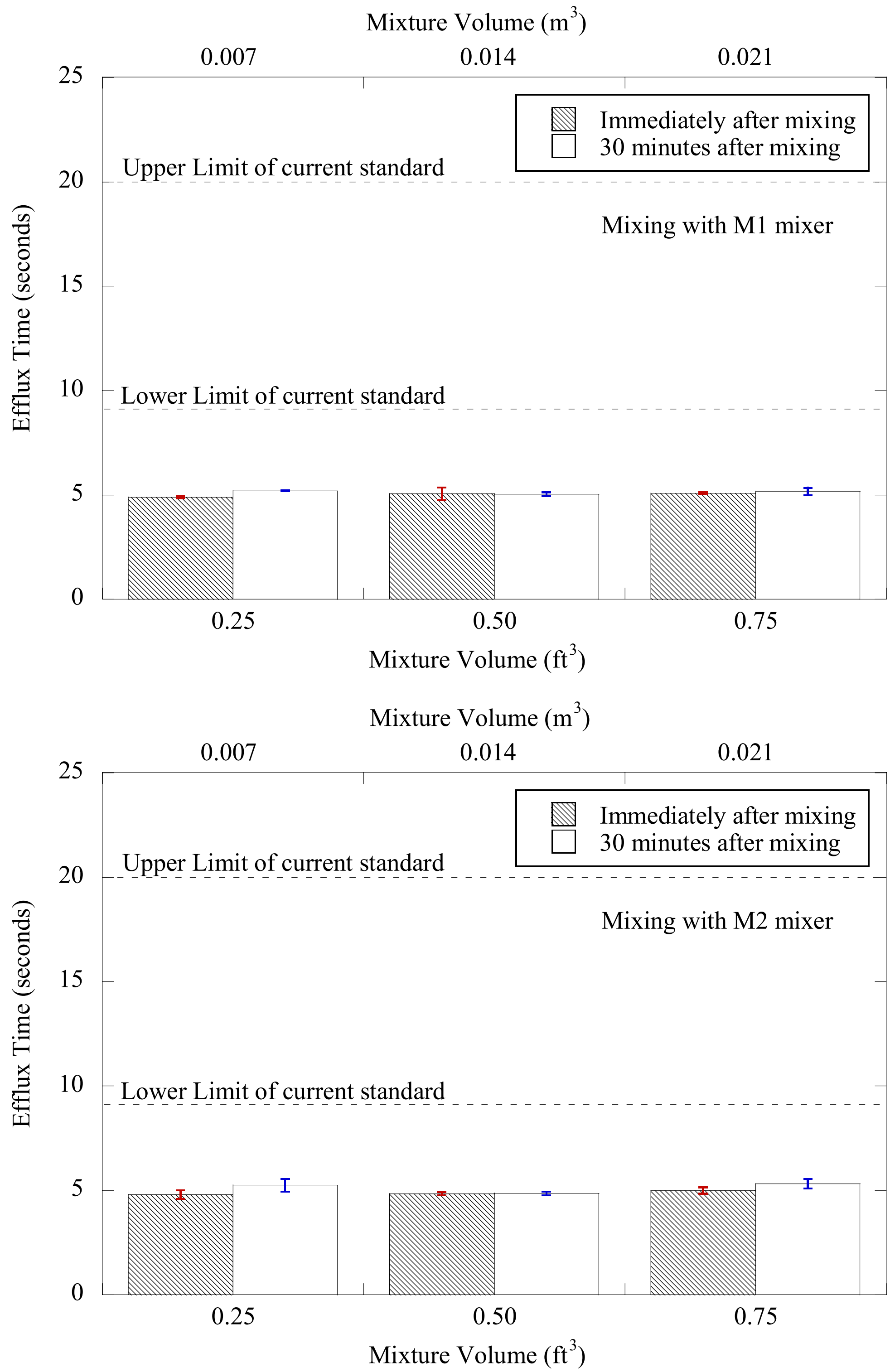


Figure 5-6. Efflux time versus the volume of mixture for Class A grout, (a) using M1 mixer and (b) using M2 mixer.

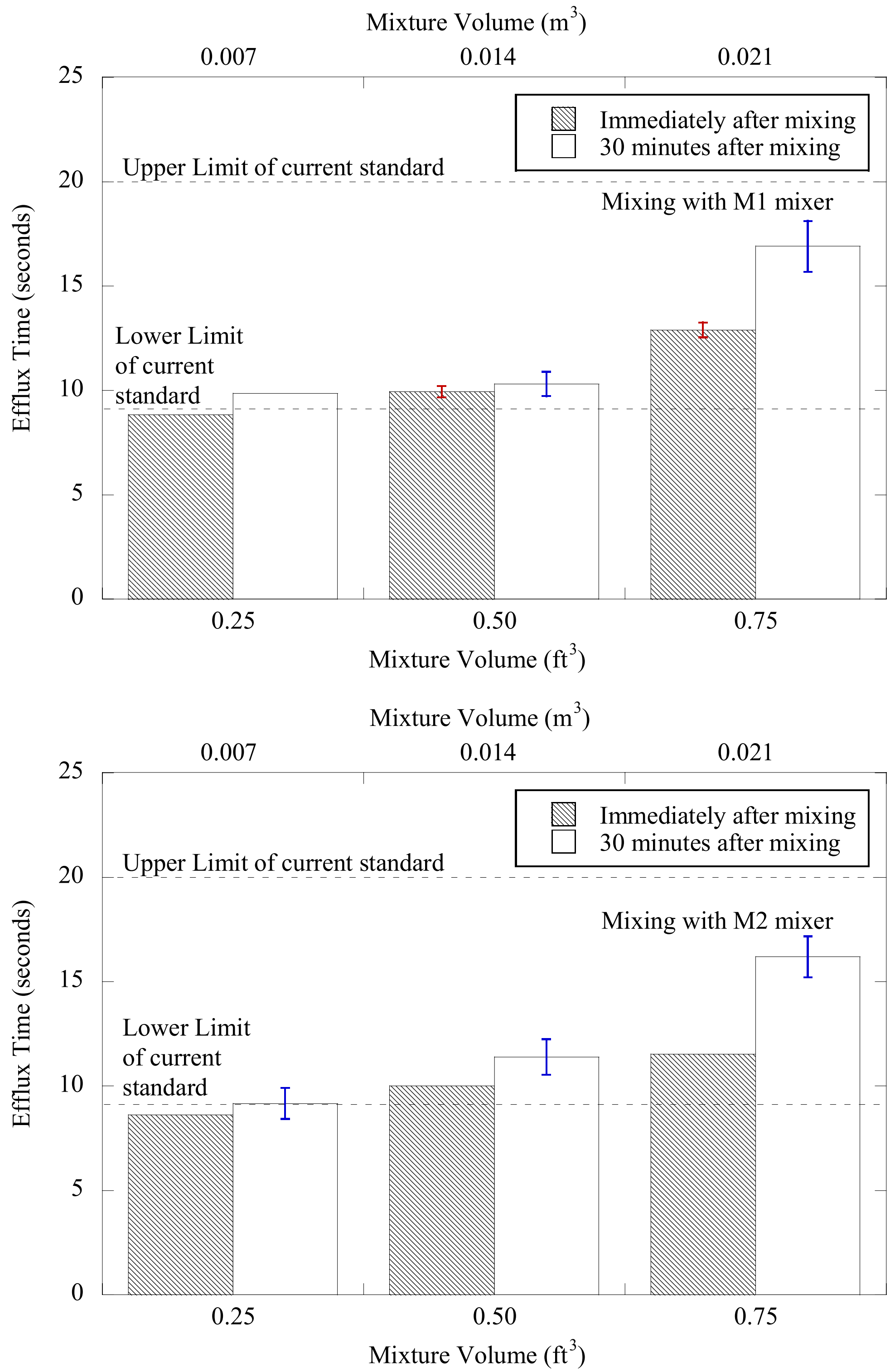


Figure 5-7. Efflux time versus the volume of mixture for Class C-1 grout (a) using M1 mixer and (b) using M2 mixer.

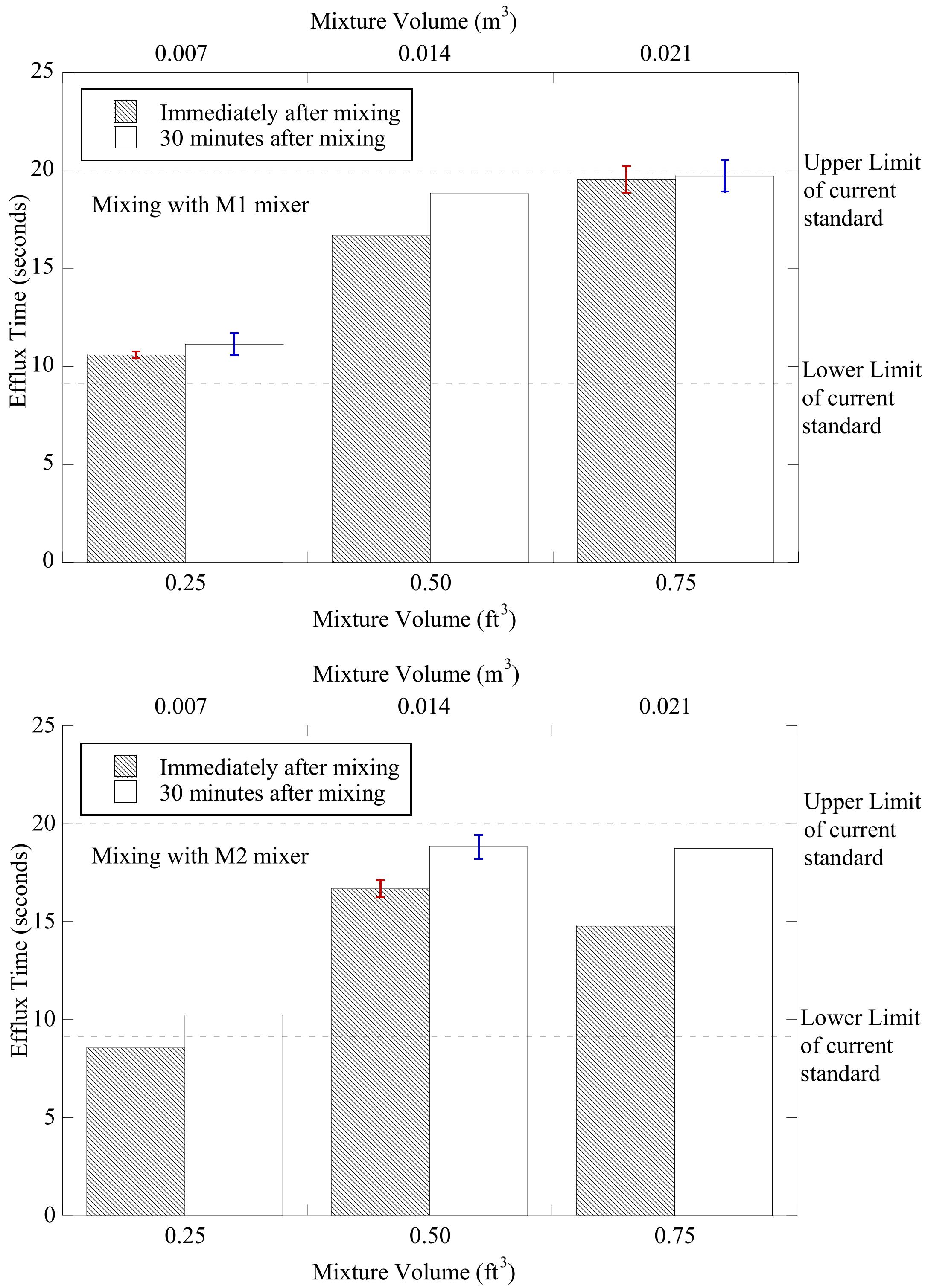


Figure 5-8. Efflux time versus the volume of mixture for Class C-2 grout, (a) using M1 mixer and (b) using M2 mixer.

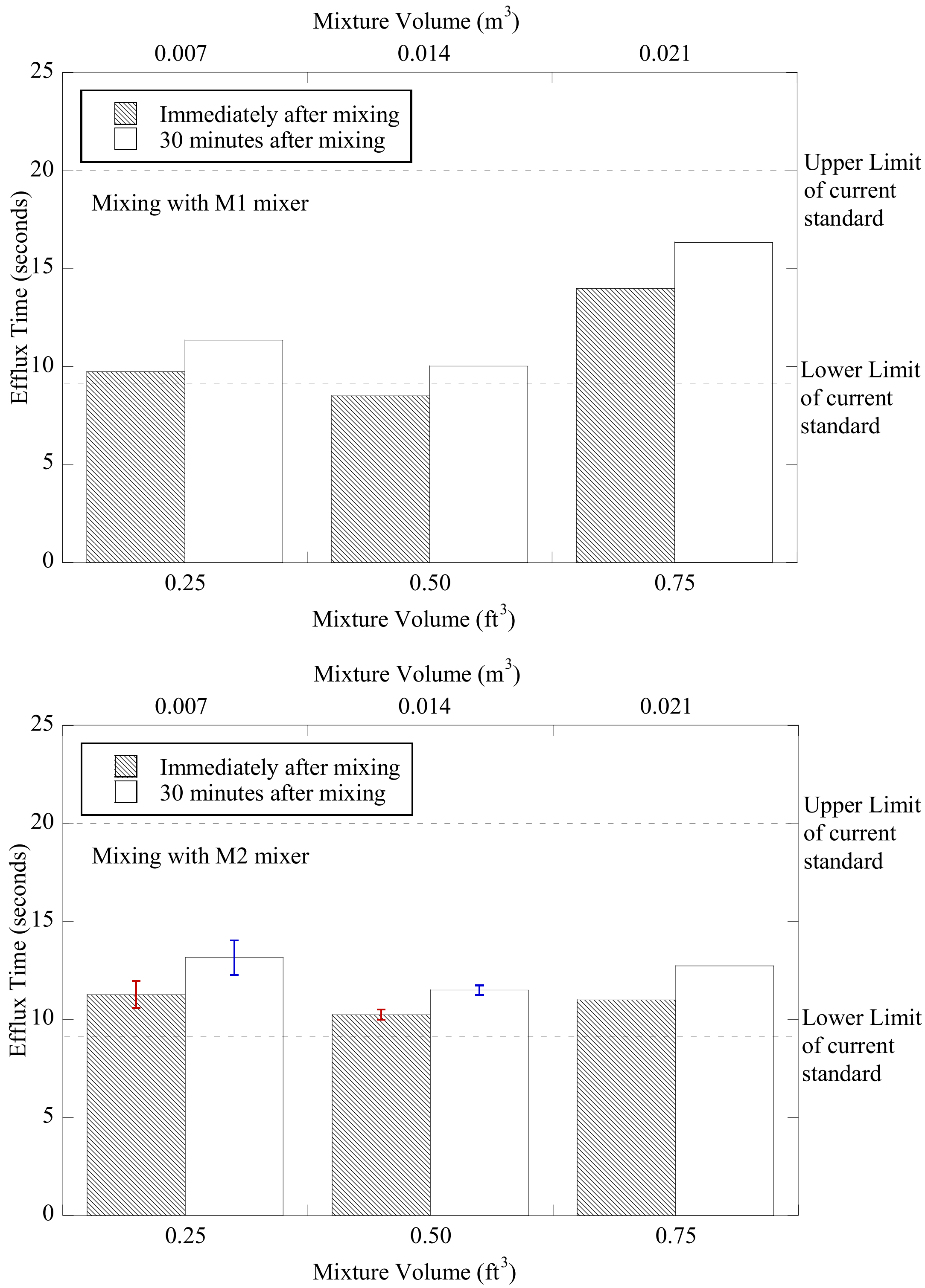


Figure 5-9. Efflux time versus the volume of mixture for Class C-3 grout, (a) using M1 mixer and (b) using M2 mixer.

A general observation can be made that as the mixture volume increases from 0.25 ft^3 (0.0071 m^3) to 0.75 ft^3 (0.0213 m^3), the efflux time increases. A comparison can be made between the efflux times of all grouts, which concludes that Class A has a lower efflux time as compared to other grouts, although Class A grout does not meet the current TxDOT minimum efflux time requirements (minimum 9 seconds).

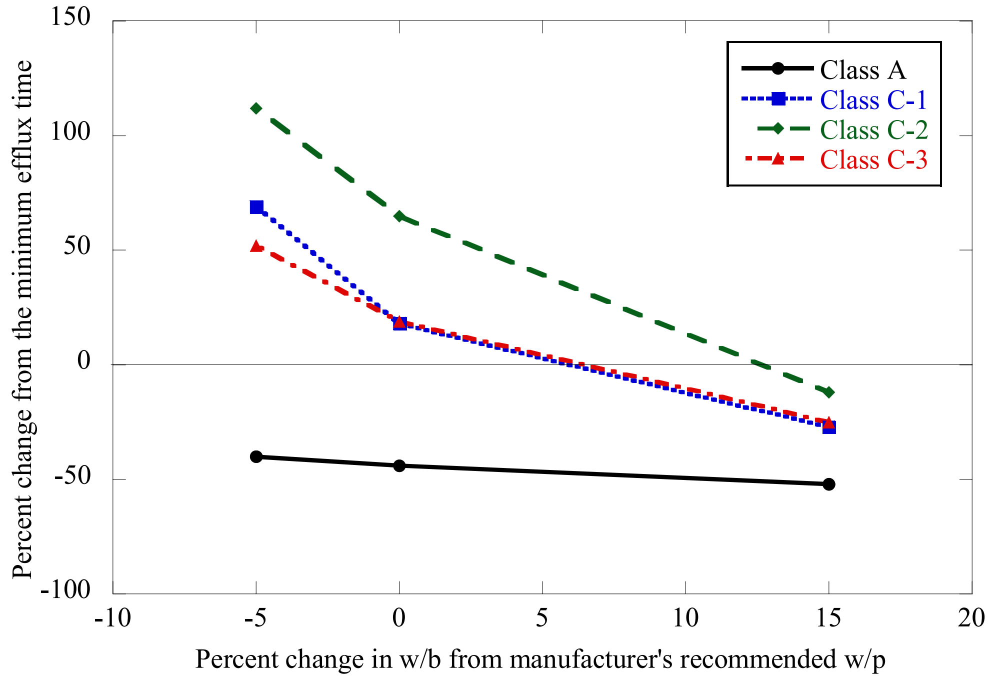
Figure 5-10 (a) and (b) show the sensitivity of efflux time as a function of w/p for the grouts mixed with M1 and M2 mixers respectively. The base case for the w/p sensitivity analysis is the manufacturer's recommended w/p for all grouts. Experiments were performed for the recommended w/p, a w/p 5% lower than that recommended by the manufacturer, and 15% higher than that recommended by the manufacturer.

From Figure 5-10, it can be seen that as the w/p increases the efflux time decreases. The Class C-1 and C-3 grouts have nearly the same efflux time for the corresponding w/p. The C-2 grout has lower efflux time when compared to the Class C-1 and C-3 grouts.

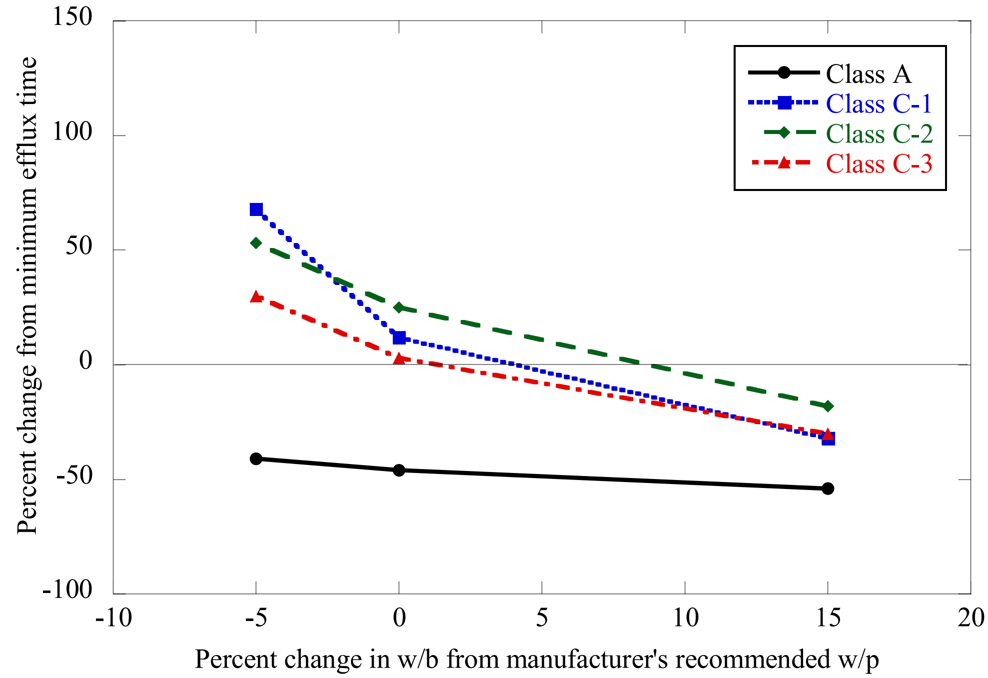
One reason for this could be that the Class C-2 grout has a manufacturer's recommended w/p of 0.26 which is lower than that for Class C-1 and C-3 grouts. It should also be pointed out that the efflux time of the grouts mixed with M2 mixer were lower than the corresponding efflux times using the M1 mixer.

The viscosity results for Class C-2 and C-3 grouts (Figures 5-4 and 5-5) also indicated that the viscosity values of Class C-2 and C-3 grouts were higher while mixing with the M1 mixer when compared to M2 mixer. A higher viscosity indicates higher efflux time due to the resulting stiff mixture. It can be concluded that mixing with a higher rpm mixer results in a more fluid mixture.

Grouts C-1, C-2, and C-3 do not meet the current TxDOT's requirements for minimum efflux time as the w/p is increased to 15% of the manufacturer's recommended w/p. It should be noted that the recommended w/p should be followed.



(a)



(b)

Figure 5-10. Efflux time sensitivity to the w/p for all four grout types (a) using M1 mixer, and (b) using M2 mixer.

Three mixture volumes were used in the test matrix to study the effect of mixing volume on the efflux time of grouts. A randomized complete block design (RCBD) model is used to test the effect of mixture volume. The linear statistical model is represented by Equation (5.6) shown below:

$$Y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij} \begin{cases} i = 1, 2, 3 \\ j = 1, 2, 3 \end{cases} \tag{5.6}$$

where μ is the overall mean efflux time, τ_i is the effect of the *i*th treatment (mixture volume), β_j is the *j*th block (w/p), and ε_{ij} is the random error term, which is assumed to be independent and normally distributed with a mean of zero and variance σ^2. To test the equality of the treatments effects (mixture volume), the RCBD is used and it is assumed that the treatment and blocks (w/p) do not interact. The testing hypotheses are shown in Equation (5.7) below:

$$\begin{aligned} &H_0 = \tau_1 = \tau_2 = \tau_3 = 0 \\ &H_1 = \tau_i \neq 0 \text{ for at least one } i \end{aligned} \tag{5.7}$$

A summary of the RCBD ANOVA results is shown in the Table 5-4. The *p*-value for the analysis performed on Class A is close to 0.05, hence assuming the test statistic it can be conclude that the mixture volume has significant on the efflux time of Class A grout. However, at a 5% level of significance, the null hypothesis cannot be rejected for any of the three Class C grouts under study. Hence, it can be concluded that the mixture volume does not significantly affects the efflux time at a 5% level of significance.

Table 5-4. Summary statistics of RCBD ANOVA test with mixture volume as treatments.

Source of Variation	Grout	F-statistic	F critical	*p*-value
Mixture Volume	Class A	6.505	6.944	0.055
	Class C-1	3.372	6.944	0.139
	Class C-2	5.907	6.944	0.064
	Class C-3	1.719	6.944	0.289

The effect of mixer type was studied to evaluate whether mixer type influences grout characteristics and to determine whether one mixer type is more effective than another. Two small mixers M1 and M2 with helical paddles were used to study the effect of the mixer type on grout characteristics. Efflux time observations were averaged from the three mixture volume test results obtained and used in statistical analysis. To study the effect of mixer type on the efflux time, a RCBD analysis of variance was performed. Equation 5.8 represents the linear statistical model:

$$Y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij} \begin{cases} i = 1,2 \\ j = 1,2,3 \end{cases} \tag{5.8}$$

where μ is an overall mean, τ_i is the effect of the *i*th treatment, β_j is the *j*th block, and ε_{ij} is the random error term, which is assumed to be normally independently distributed with mean zero and variance σ^2. The testing hypotheses are shown in Equation 5.9:

$$\begin{aligned} &H_0 = \tau_1 = \tau_2 = 0 \\ &H_1 = \tau_i \neq 0 \text{ for at least one } i \end{aligned} \tag{5.9}$$

A summary of the RCBD ANOVA results is shown in the Table 5-5. The test results indicate that, at a 5% level of significance the null hypothesis cannot be rejected, for any of the Class C grouts under study. It can be concluded that the mixer types used in the study do not significantly affects the efflux time for Class C grouts. Efflux time of the Class A grout, on the other hand, is significantly affected by the mixer type at 5% level of significance.

Table 5-5. Summary statistics for RCBD ANOVA with mixer type as treatments.

Source of Variation	Grout	F-statistic	F critical	*p*-value
Mixer Type	Class A	158.281	18.513	0.006
	Class C-1	6.675	18.513	0.123
	Class C-2	5.312	18.513	0.148
	Class C-3	1.791	18.513	0.313

It was derived from the analysis shown above that the mixer type has no significant effect on the fluidity of Class C grouts, which means that the any of the two mixers (M1 and M2) can be used for mixing the grout. However, from a practical point of view, it is advisable to use the higher speed mixer (M2 mixer) in order to achieve a more homogenous and consistent grout mixture.

There are some issues associated with the M2 mixer. The M2 mixer overheated when more than one bag of grout mixture was mixed. This problem was solved by using two similar mixers and using the second one when the first mixer started overheating. Hence, it is recommended that if the M2 mixer is used then:

- not more than one bag of grout should be mixed at once
- have two mixers and use one after the other in case of overheating of the mixer

Grout fluidity is an indirect measure of the viscosity of the grout and a correlation may be present between these characteristics. To carry out correlation analyses between the efflux time and viscosity, viscosity measurements immediately after mixture (time zero) and 30 minutes after the mixture were extracted from the collected data. Then a correlation analysis was performed between the two corresponding measurements for each grout type.

The correlation coefficients between the efflux time and the grout viscosity for all grouts were evaluated. The correlation coefficient typically ranges from -1 to 1. A correlation coefficient of zero indicates no correlation between the efflux time and viscosity, a correlation coefficient close to 1 indicates a good positive correlation between the efflux time and viscosity whereas a correlation coefficient close to negative one (-1) indicates a good negative correlation between the same.

Tables 5-6 and 5-7 illustrate the correlation coefficients for the Class A, C-2, and C-3 grouts mixed with the different mixers. The Class C-1 grout is not included in the correlation analysis because the viscosity tests were not performed on the Class C-1 grout. The correlation coefficients between the efflux time and viscosity of the grouts came out to be greater than 0.7 which demonstrate that a higher efflux time implies higher viscosity. It can be concluded that a lower efflux time indicates in lower viscosity which corresponds to higher fluidity.

Table 5-6. Correlation coefficients between efflux time and viscosity for Class A, C-2, and C-3 grouts mixed with M1 mixer.

Viscosity		Efflux Time					
		Class A		Class C-2		Class C-3	
		0 min	30 min	0 min	30 min	0 min	30 min
Class A	0 min	0.979	-	-	-	-	-
	30 min	-	0.904	-	-	-	-
Class C-2	0 min	-	-	0.981	-	-	-
	30 min	-	-	-	0.989	-	-
Class C-3	0 min	-	-	-	-	0.782	-
	30 min	-	-	-	-	-	0.764

Table 5-7. Correlation coefficients between efflux time and viscosity for Class A, C-2, and C-3 grouts mixed with M2 mixer.

Viscosity		Efflux Time					
		Class A		Class C-2		Class C-3	
		0 min	30 min	0 min	30 min	0 min	30 min
Class A	0 min	0.774	-	-	-	-	-
	30 min	-	0.533	-	-	-	-
Class C-2	0 min	-	-	0.986	-	-	-
	30 min	-	-	-	0.919	-	-
Class C-3	0 min	-	-	-	-	0.850	-
	30 min	-	-	-	-	-	0.841

While preparing the grout mixtures, the actual rpms of both mixers were measured using a tachometer. A correlation analysis was performed to study the correlation between the actual mixer rpm and efflux time of the resulting mixture. The correlation coefficients between the efflux time and the actual rpm for all grouts were evaluated and are shown in Tables 5-8 and 5-9. Results show the correlation coefficient from the M1 and M2 mixers for the Class A, C-1, C-2 and C-3 grouts.

Table 5-8. Correlation coefficients between efflux time and mixer rpm for Class A, C-1, C-2, and C-3 grouts mixed with M1 mixer.

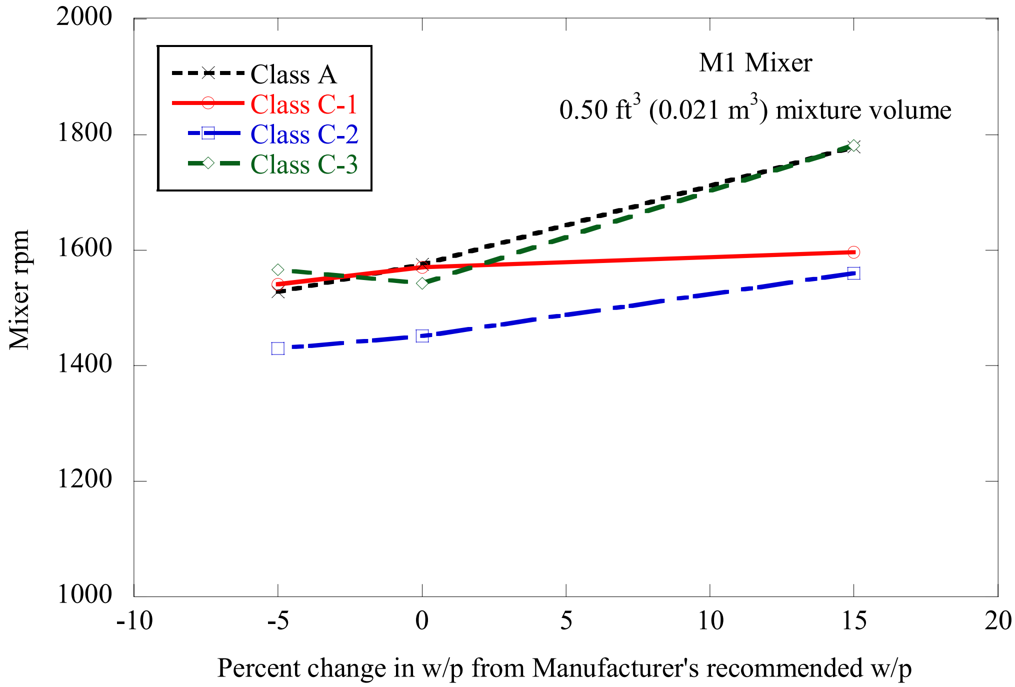
Actual rpm	Efflux Time			
	Class A	**Class C-1**	**Class C-2**	**Class C-3**
Class A	-0.4735			
Class C-1		-0.4738		
Class C-2			-0.4172	
Class C-3				-0.2028

Table 5-9. Correlation coefficients between efflux time and mixer rpm for Class A, C-1, C-2, and C-3 grouts mixed with M2 mixer.

Actual rpm	Efflux Time			
	Class A	**Class C-1**	**Class C-2**	**Class C-3**
Class A	-0.4332			
Class C-1		-0.1989		
Class C-2			-0.6853	
Class C-3				-0.4237

The correlation coefficients between the efflux time and mixer rpm for most grouts are between -0.5 and 0 which indicates a weak negative correlation between the efflux time and actual rpm. This negative correlation between the efflux time and mixer rpm is expected because as the mixer rpm increases the mixture becomes more fluid which in turn results in a mixture with a lower efflux time. Hence, the efflux time of the mixture decreases as the mixer rpm increases.

The speed of the mixer depends on the w/p and the volume of the mixture. When the w/p increases, the mixer rotates at a faster speed. When the mixture volume increases the mixer rotating speed decreases. Figure 5-11 shows the variation of mixer rpm with the change in w/p for the M1 and M2 mixers. It can be concluded from the results that as the w/p increases the mixer rpm increases. Similarly Figure 5-12 shows the variation of mixer rpm as the volume of mixture changes from 0.25 ft^3 (0.007 m^3) to 0.75 ft^3 (0.021 m^3) for M1 and M2 mixers.



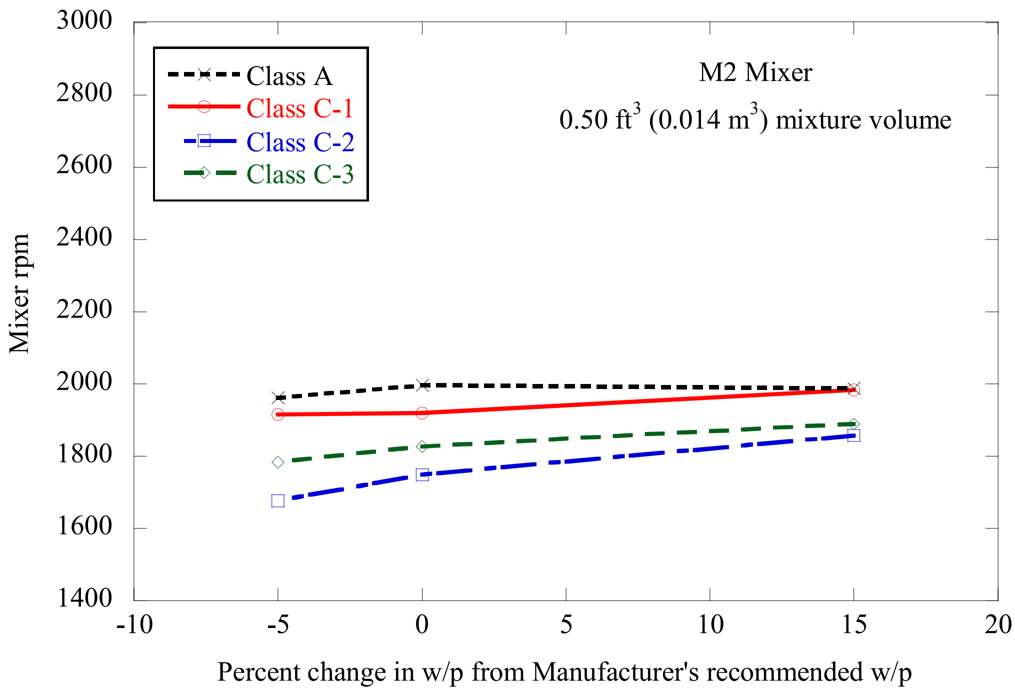


Figure 5-11. Change in mixer speed with the grout's w/p for both (a) M1 and (b) M2 mixers.

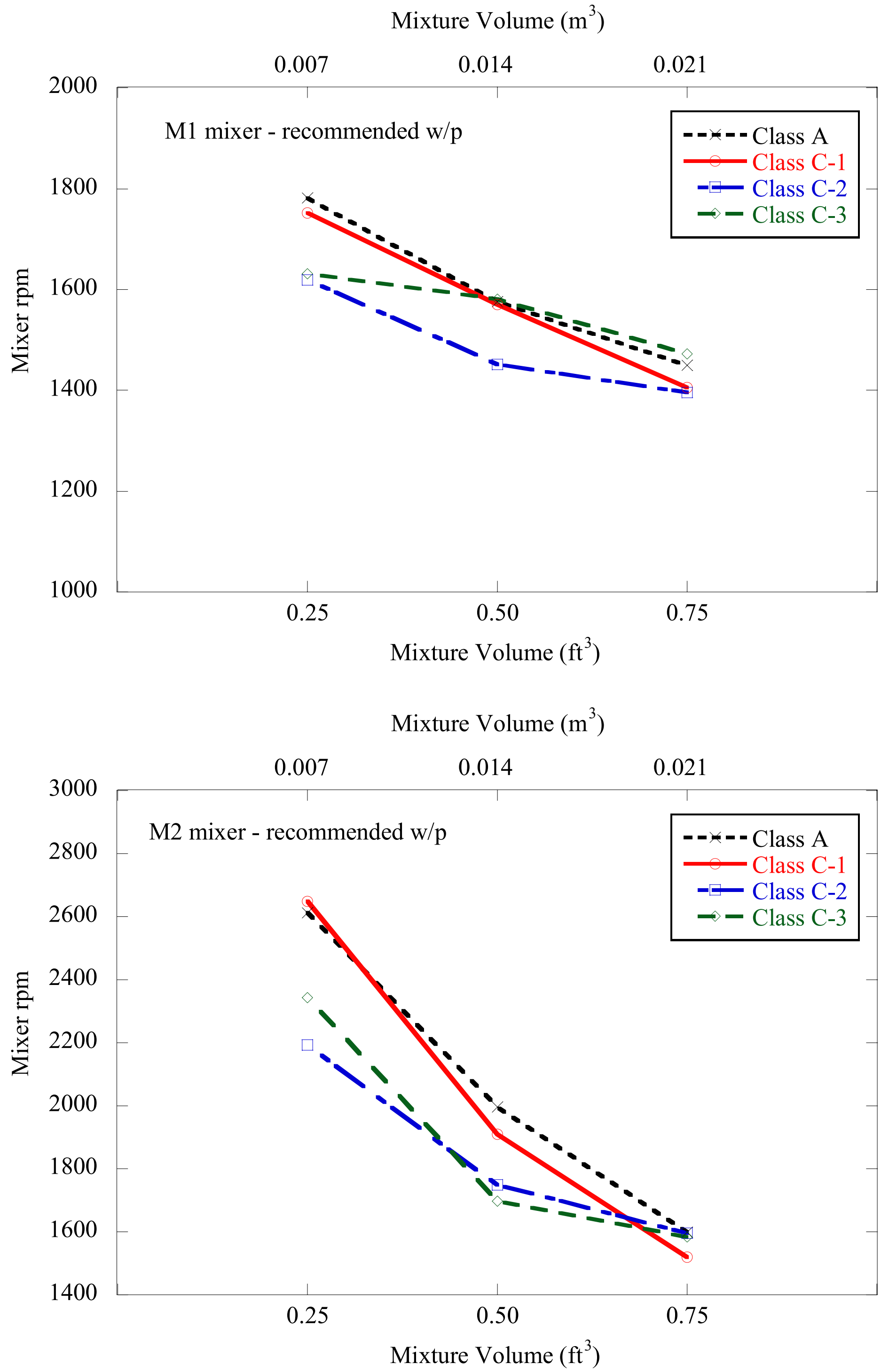


Figure 5-12. Change in mixer RPM with mixture volume for both (a) M1 and (b) M2 mixers.

M1 mixer shows more scatter when compared to the M2 mixer results for increasing w/p. However, the M2 mixer shows more scatter when compared to M1 mixer as the mixture volume changes. Because a higher rpm mixer is desirable to achieve high shearing during mixing of the M2 mixer may provide a better shearing action with the higher average rpm when compared to the M1 mixer.

5.1.4. Wet Density

The Baroid mud balance was used to measure the wet density of freshly prepared grout mixture. The average grout density and the range of grout density obtained from the tests for the recommended w/p mixtures are presented in the Table 5-10. The test results indicate that the range of Class C-1 and C-3 grouts is narrow which shows very little variation of grout density.

These grout ranges were calculated by performing repeat tests on all grouts to study the variability of the mud balance test. These lower and upper grout ranges were approximately plus or minus one standard deviation ($\pm 1\sigma$) which is approximately equal to plus or minus 0.5 percent of the mean grout wet density.

Table 5-10. Average grout density measured using Baroid mud balance.

Grout type	Density		Density Range	
	lb/gal	g/cm^3	Minimum (lb/gal)	Maximum (lb/gal)
Class A	15.62	1.87	15.5	15.7
Class C-1	17.57	2.10	17.5	17.6
Class C-2	17.55	2.10	17.4	17.7
Class C-3	16.35	1.96	16.3	16.4

To determine the relationship between the w/p, dry density, and the wet density, tests were performed to evaluate the dry density as described in the section 3.3.4. Table 5-11 shows the dry density for Class C grouts along with their corresponding manufacturer's recommended w/p and wet densities.

Table 5-11. Dry and wet densities of Class C grouts along with corresponding manufacturer's recommended w/p.

Grout type	w/p	Dry Density		Wet Density	
		lb/gal	g/cm^3	lb/gal	g/cm^3
Class C-1	0.30	7.1	0.85	17.5	2.10
		7.0	0.84	17.5	2.10
		7.1	0.85	17.6	2.11
Class C-2	0.26	9.1	1.09	17.4	2.08
		9.1	1.09	17.6	2.11
		9.0	1.08	17.5	2.10
Class C-3	0.27	8.2	0.98	16.3	1.95
		7.9	0.95	16.4	1.97
		8.1	0.97	16.3	1.95

Using the observations shown in Table 5-11, the following model was developed to predict the theoretical wet density of the resultant grout mixture:

$$\rho_{\text{predicted}} = \theta_0 + \theta_1 (\text{w/p}) + \theta_2 (\rho_{\text{dry}}) + \sigma\varepsilon \tag{5.10}$$

where $\rho_{\text{predicted}}$ is the theoretical wet density predicted by the model, ρ_{dry} is the grout's dry density, θ_0, θ_1, and θ_2, are model parameters, σ is the model error and ε is the random error term and assumed to be normally distributed with a zero mean and unit standard deviation. The term $\sigma\varepsilon$ is collectively called as model error.

The posterior statistics of the wet density model are shown in Table 5-12. The regression coefficients for the linear regression model are shown in the column 2. A *t*-test was also performed to determine whether the independent model variables (w/p and the ρ_{dry}) are significant. The *p*-values show that at 5% level of significance, the model variables are significant and the linear regression model holds good. The R^2 value for the regression model came out to be 0.87 which indicates that the model accounts for about 87% of the variability in the wet density.

Table 5-12. Posterior statistics of the wet density model.

Model Name	MAPE (%)	Parameters	Mean	Standard Deviation	CoV	Correlation Coefficients between θ_i	
						θ_0	θ_1
Wet Density	1.02	θ_0	-28.4	9.1	-0.32	1	
		θ_1	104.6	20.7	0.20	-0.99	1
		θ_2	2.1	0.4	0.21	-0.98	0.96

The mean absolute percent error (MAPE) of the wet density model is 1.02% which is a reasonable value. The model standard deviation, σ, is also reasonable (i.e., 0.31) considering the limited amount of data available and the inherent scatter observed among data points.

The wet density model developed to predict the grout's wet density is given by the Equation 5.11:

$$\rho_{\text{predicted}} = -28.4 + 104.6\left(\text{w/p}\right) + 2.1\left(\rho_{\text{dry}}\right) \tag{5.11}$$

Using this linear model shown in Equation 5.11 the grout's wet density can be predicted by using the w/p and dry density and can be compared with the observed grout's wet density (ρ_{observed}) measured in the field using Baroid mud balance. The validation plot for wet density model is shown in Figure 5-13. This plot indicates that the model provides a reasonably good prediction of the observed grout's wet density.

Based on the accuracy of the model, it can be concluded that if the ρ_{observed} falls within the one standard deviation region (σ = ±0.31) of $\rho_{\text{predicted}}$ then no serious alteration in the grout's w/p is observed in the field. Equation 5.12 presents the criterion relating the ρ_{observed} (measured using Baroid mud balance in the field) with $\rho_{\text{predicted}}$ (calculated using the Equation 5.11).

$$\rho_{\text{observed}} = \rho_{\text{predicted}} \pm 0.31 \tag{5.12}$$

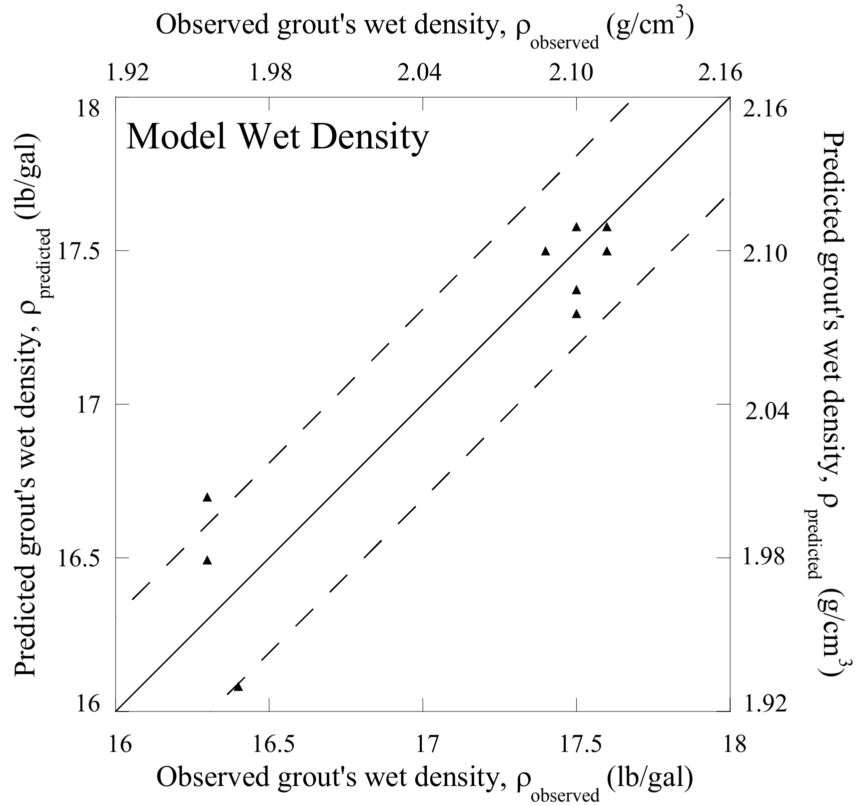


Figure 5-13. Validation plot for the wet density model.

The Baroid mud balance test can be used in the field as a quality control measure. Any significant change in grout wet density can be determined instantly and necessary actions could be taken to ensure proper grouting of PT ducts. Therefore, the Baroid mud balance test is recommended in the field. The observed wet density can be compared with the manufacturer’s specified wet density corresponding to the w/p.

5.1.5. Initial Setting Time

The initial setting time results for the grouts are shown in Figures 5-14 and 5-15 when mixing with M1 and M2 mixers respectively. All grouts used in the research (Class A, C-1, C-2, and C-3 grouts) exhibit an initial setting time between 4 hours to 11 hours which fulfills the current TxDOT requirements.

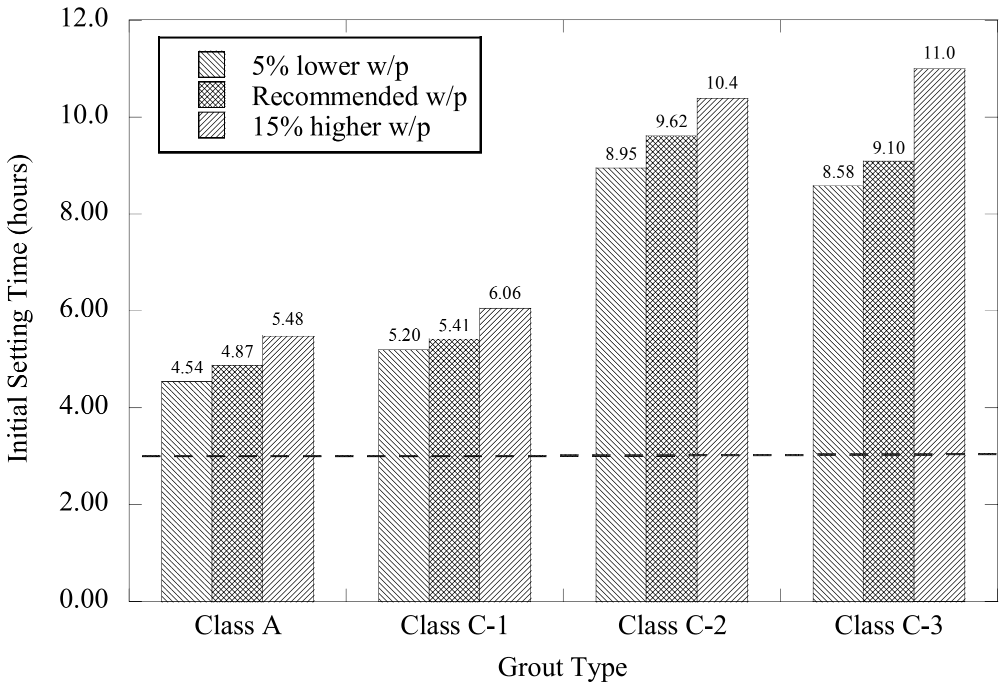


Figure 5-14. Initial setting time for Class A, C-1, C-2 and C-3 grouts when mixed with M1 mixer.

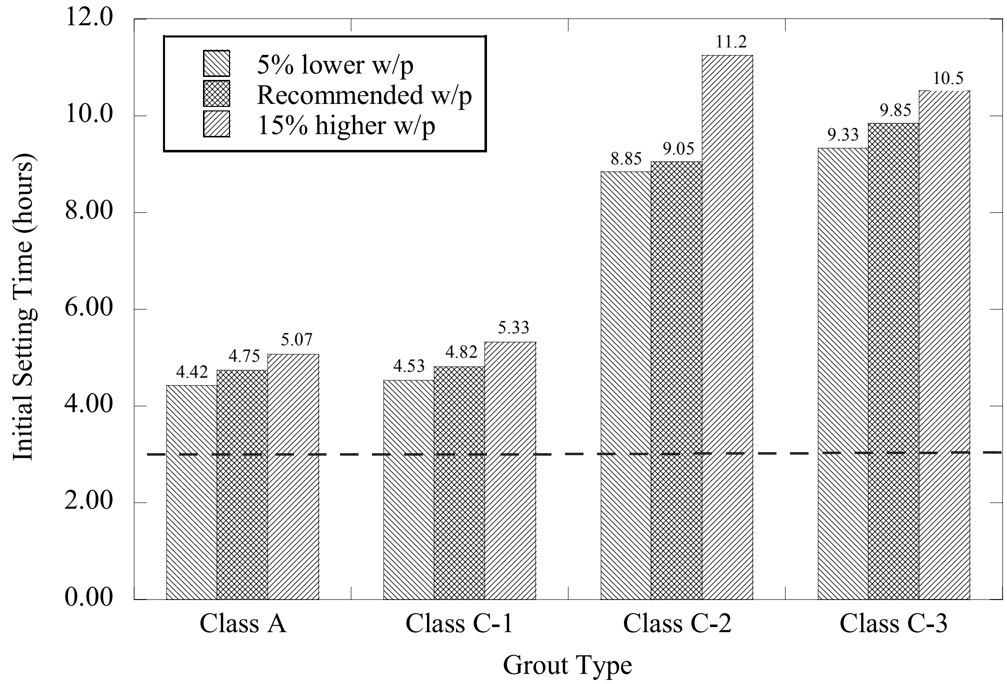


Figure 5-15. Initial setting time for Class A, C-1, C-2 and C-3 grouts when mixed with M2 mixer.

Although initial setting time is not related to the workable time of the grout, it is assumed that grouts with a low initial setting time tends to stiffen early, thereby reducing the time available to successfully place the grout without significant loss in other grout characteristics. Because all initial setting tests were performed in the laboratory where the temperature and other climatic conditions were controlled, the conditions may not be controlled in the field while grouting the PT ducts. The temperature in the field may be higher than the laboratory temperature which can accelerate the initial setting of grouts. Hence, from a practical point of view, a very less time will be available to place the grout without affecting the grout characteristics.

It is therefore recommended that the minimum required lower initial setting time should be increased from three hours to four hours. It is assumed that there is a chance that an increase in the initial setting time can increase the time available to place the grout in the field.

5.2. Hardened Characteristics

Compressive strength and dimensional stability results are presented in this section.

5.2.1. Compressive Strength

The compressive strength test was performed on all four grouts for five different test ages following the Tex-442-A. At each test age, an average of 3 cube strengths was reported. Figure 5-16, 5-17, and 5-18 show the average compressive strength for all grouts at 1, 3, 7, 28, and 56 day test ages. Values are reported for the manufacturer's recommended w/p, and -5% and +15% of the manufacturer's recommended w/p. Values were averaged for the M1 and M2 mixers.

One-day strengths were higher in the Class C-1 grout while at 3, 7, 28, and 56 days, the average compressive strength for both Class C-1 and C-2 grouts are nearly the same. The Class C-3 grout results indicate low strengths when compared to the Class C-1 and C-2 grouts at all five sample ages. The Class A grout results in a much lower strength when compared to the Class C-1, C-2, and C-3 grouts.

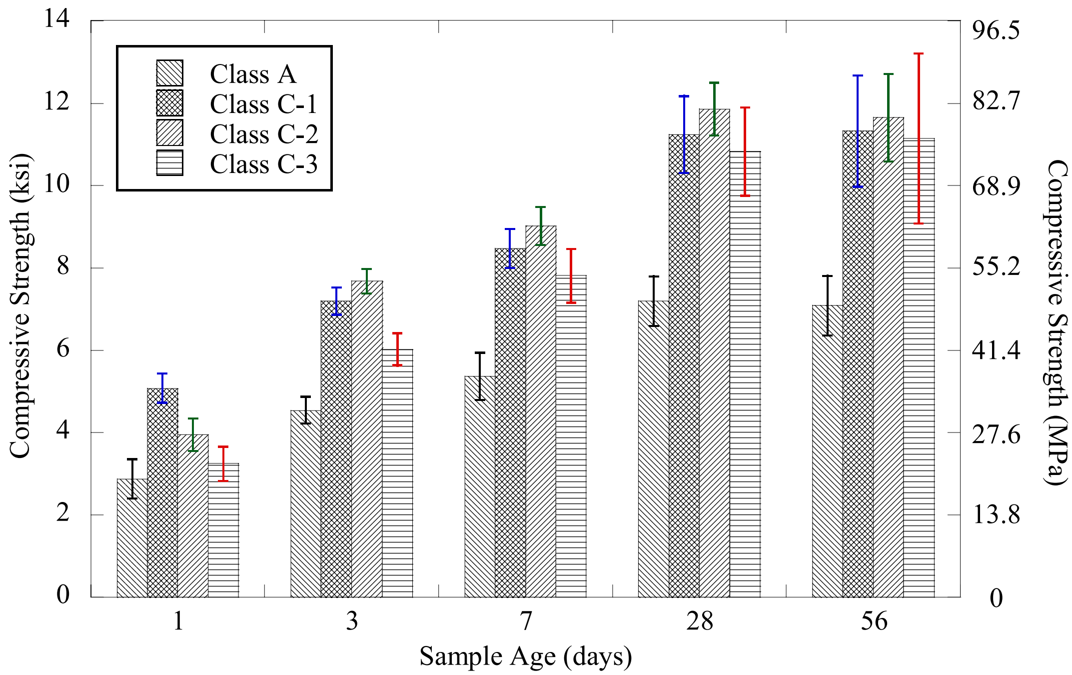


Figure 5-16. Compressive strength results at various sample ages for four grout types at low w/p.

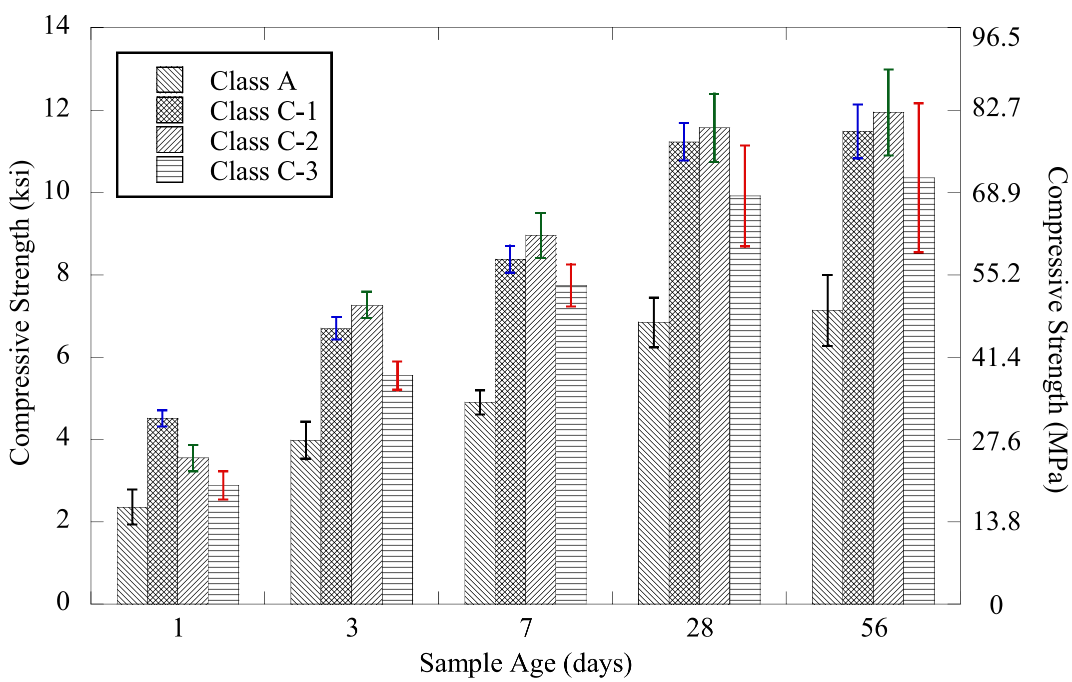


Figure 5-17. Compressive strength results at various sample ages for the grout types at recommended w/p.

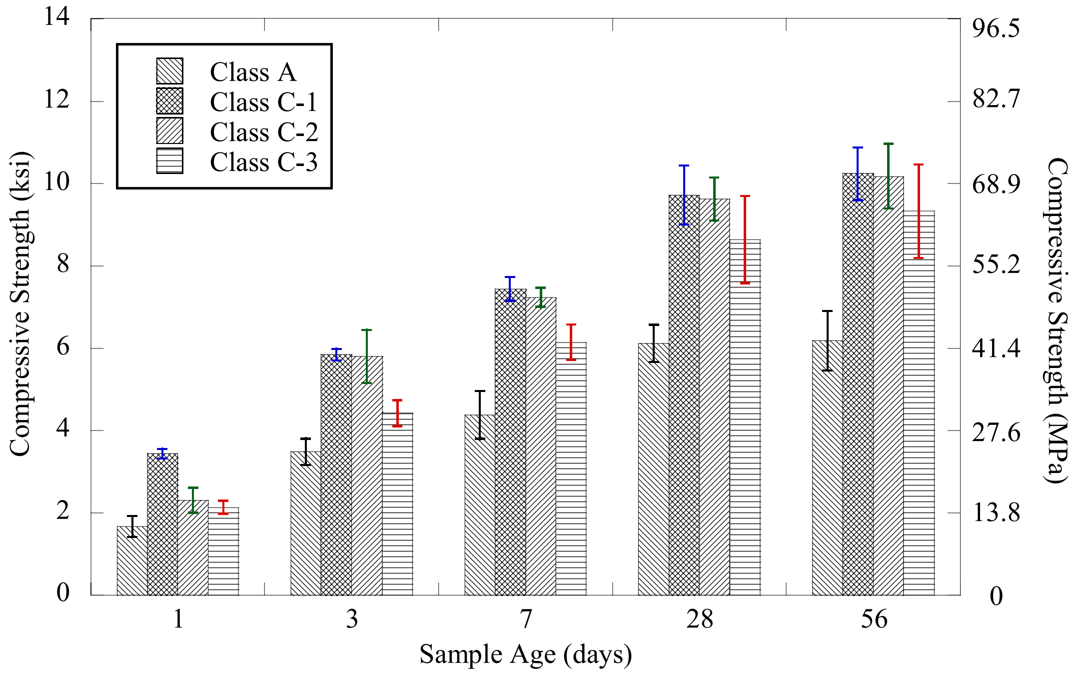


Figure 5-18. Compressive strength results at various sample ages for the grout types at the high w/p.

In some of the Class C grouts, SCMs may have been included to improve the grout's early strength characteristics. A higher compressive strength, however, may not enhance the performance of the grout in PT applications. To evaluate the effect of mixer type, mixture volume, w/p, and sample age on the grout's compressive strength, a four-factor-factorial fixed-effects ANOVA was defined.

The four-factor-factorial experiment was considered to analyze the effect of all factors on the grout's compressive strength. The four factors are mixer type (MIXER), volume of mixture (VOL), w/p of the mixture (WP), and the age of the sample (AGE). The four-factor-factorial experiment also analyzes the interactions among the factors along with their individual effects. The aim of this analysis is to determine the effect of the four factors on the compressive strength of the grouts. Interactions such as the MIXER-VOL and MIXER-WP are important for the research as one mixer type may perform better than the other as the mixture volume changes. Similarly, the mixer's performance may also change as the grout's w/p is altered. Other two-way interactions such as MIXER-AGE, VOL-AGE etc. and other higher order interactions are less significant in determining the suitable mixer type that can produce better grout mixture. For the sake of simplicity, all other two-way, three-way and four-way interactions were ignored. The four-factor-factorial model is defined as:

$$Y_{ijklm} = \mu + \tau_i + \alpha_j + \beta_k + \gamma_l + (\tau\alpha)_{ij} + (\tau\beta)_{ik} + \varepsilon_{ijklm} \begin{cases} i = 1,2 \\ j = 1,2,3 \\ k = 1,2,3 \\ l = 1,2,\ldots,5 \\ m = 1,2,3 \end{cases} \quad (5.13)$$

where μ is the overall mean effect, τ_i is the effect of the *i*th level of mixer type, α_i is the effect of the *j*th level of mixture volume, β_j is the *k*th effect ofw/p and γ_k is the *l*th effect of sample age, $(\tau\alpha)_{ij}$ is the effect of the interaction between mixer type and mixture volume, $(\tau\beta)_{ik}$ is the effect of the interaction between mixer type and w/p, and ε_{ijklm} is a random error component having a normal distribution with mean zero and variance σ^2.

The null and alternate hypotheses for all factors are as follows:

$$
\begin{aligned}
&1.\ H_0 = \tau_1 = \tau_2 = 0 && \text{(no main effect of mixer type)} \\
&\quad H_1 = \tau_i \neq 0 \text{ at least one } i \\
&2.\ H_0 = \alpha_1 = \alpha_2 = \alpha_3 = 0 && \text{(no main effect of mixture volume)} \\
&\quad H_1 = \alpha_j \neq 0 \text{ at least one } j \\
&3.\ H_0 = \beta_1 = \beta_2 = \beta_3 = 0 && \text{(no main effect of w/p)} \\
&\quad H_1 = \beta_k \neq 0 \text{ at least one } k \\
&4.\ H_0 = \gamma_1 = \gamma_2 = \ldots = \gamma_5 = 0 && \text{(no main effect of sample age)} \\
&\quad H_1 = \gamma_l \neq 0 \text{ at least one } l \\
&5.\ H_0 = (\tau\alpha)_{11} = (\tau\alpha)_{12} = (\tau\alpha)_{23} = 0 && \text{(no interaction)} \\
&\quad H_1 = \text{at least one } (\tau\alpha)_{ij} \neq 0 \\
&6.\ H_0 = (\tau\beta)_{11} = (\tau\beta)_{12} = (\tau\beta)_{23} = 0 && \text{(no interaction)} \\
&\quad H_1 = \text{at least one } (\tau\beta)_{ik} \neq 0
\end{aligned}
\tag{5.14}
$$

Once the hypotheses are defined, fixed effects ANOVA was performed to test these hypotheses on the grouts. Tables 5-13, 5-14, 5-15, and 5-16 summarize the ANOVA results obtained while studying the effect of various factors on the compressive strength of the grouts. The *p*-values for all the test statistics are shown in the last column of table. The *p*-values reveal that at a 5% level of significance there is no main effect of mixer type or mixture volume (i.e., *p*-value > α). It also shows that the w/p and sample age have a significant effect on the grout's compressive strength which was expected.

The two interactions, one between the mixer type and mixture volume and the other between the mixer type and the w/p were also evaluated to study the combined effect. The *p*-values shown in the table reveals that there is no significant interaction among these pairs.

Table 5-13. ANOVA computations for the hypotheses for Class C-1 grout.

Source	Degrees of Freedom	Type III Sum of Squares	Mean Square	F statistic	*p*-value
MIXER	1	18096	18096	0.05	0.8205
VOL	2	541745	270873	0.77	0.4628
WP	2	91477275	45738637	130.47	<.0001
AGE	4	1721932257	430483064	1227.97	<.0001
MIXER*VOL	2	1156711	578355	1.65	0.1941
MIXER*WP	2	130394	65197	0.19	0.8304

Table 5-14. ANOVA computations for the hypotheses for Class C-2 grout.

Source	Degrees of Freedom	Type III Sum of Squares	Mean Square	F statistic	*p*-value
MIXER	1	6444098	6444098	18.02	<.0001
VOL	2	445593	222797	0.62	0.537
WP	2	178057154	89028577	248.91	<.0001
AGE	4	2.339E+09	584853109	1635.2	<.0001
MIXER*VOL	2	4275840	2137920	5.98	0.003
MIXER*WP	2	741983	370992	1.04	0.356

Table 5-15. ANOVA computations for the hypotheses for Class C-3 grout.

Source	Degrees of Freedom	Type III Sum of Squares	Mean Square	F statistic	*p*-value
MIXER	1	17550778	17550778	21.84	<.0001
VOL	2	1440247	720123	0.9	0.4095
WP	2	132518900	66259450	82.44	<.0001
AGE	4	2128961223	532240306	662.24	<.0001
MIXER*VOL	2	23679875	11839938	14.73	<.0001
MIXER*WP	2	1799269	899635	1.12	0.3281

Table 5-16. ANOVA computations for the hypotheses for Class A grout.

Source	Degrees of Freedom	Type III Sum of Squares	Mean Square	F statistic	*p*-value
MIXER	1	93305.2	93305.2	0.35	0.5546
VOL	2	1449147	724573	2.72	0.0679
WP	2	50499058	25249529	94.71	<.0001
AGE	4	782453651	195613413	733.76	<.0001
MIXER*VOL	2	2932457	1466228	5.5	0.0046
MIXER*WP	2	3765538	1882769	7.06	0.001

To determine which treatment pairs are significantly different, *Fisher's least significant difference (LSD)* method is used. The null hypothesis for comparing all pairs of means (μ_i, μ_j) by the Fisher's LSD is:

$$H_0 : \mu_i = \mu_j \quad \text{for all}\, i \neq j \tag{5.15}$$

According to the Fisher's LSD, the pair of means μ_i, μ_j would be declared significantly different if

$$|\,\bar{y}_{i.} - \bar{y}_{j.}\,| > \text{LSD} \tag{5.16}$$

where the LSD, is defined as:

$$\text{LSD} = t_{\alpha/2, a(n-1)} \sqrt{\frac{2MS_E}{n}} \tag{5.17}$$

where $t_{\alpha/2, a(n-1)}$ is a two sided t-statistic with α level of significance, a is the number of levels in a particular treatment, n is the sample size, and MS_E is the mean square error (Montgomery and Runger 2007).

Table 5-17 summarizes the results obtained from Fisher's LSD test to identify which treatment level means are different for all grouts. The column 3 of the table lists the treatment levels for all treatment types and column 4 lists the Fisher's least LSD in compressive strength for each treatment evaluated using Equation 5.14 to determine whether the treatment levels are significantly different.

The last column of the Table 5-17 reveals that for all grouts, the mixer type and mixture volume does not significantly affect the compressive strength, assuming a 0.05 level of significance. It is already well understood that the compressive strength increases as the w/p decreases. But in this experiment, the w/p values assessed are the recommended w/p, 5% lower than recommended w/p, and 15% higher than recommended w/p. So, the recommended w/p and 5% lower than recommended w/p does not significantly affect the compressive strength at the 5% level of significance, although the compressive strength corresponding to the lower w/p is slightly higher than the recommended w/p. Fisher's LSD method also reveal that the 28 day and 56 day compressive strength are not significantly different at the 5% level of significance, indicating only small quantities of fly ash are likely present.

Table 5-17. Summary of multiple comparisons following the ANOVA based on LSD.

Grout (1)	Treatment (2)	Treatment Levels (3)	Result (4)
Class A	Mixer type	M1, M2	No significant difference
	Mixture volume	0.25, 0.50, 0.75	No significant difference
	w/p	0.41, 0.44, 0.51	0.41 and 0.44 not significantly different
	Age	1, 3, 7, 28, 56	28 day and 56 day strength not significantly different
Class C-1	Mixer type	M1, M2	No significant difference
	Mixture volume	0.25, 0.50, 0.75	No significant difference
	w/p	0.27, 0.30, 0.35	0.27 and 0.30 not significantly different
	Age	1, 3, 7, 28, 56	28 day and 56 day strength not significantly different
Class C-2	Mixer type	M1, M2	No significant difference
	Mixture volume	0.25, 0.50, 0.75	No significant difference
	w/p	0.25, 0.26, 0.30	0.25 and 0.26 not significantly different
	Age	1, 3, 7, 28, 56	28 day and 56 day strength not significantly different
Class C-3	Mixer type	M1, M2	No significant difference
	Mixture volume	0.25, 0.50, 0.75	No significant difference
	w/p	0.26, 0.27, 0.31	0.41 and 0.44 not significantly different
	Age	1, 3, 7, 28, 56	28 day and 56 day strength not significantly different

5.2.2. Dimensional Stability

The dimensional stability of cylindrical specimens was measured for all grouts following ASTM C1090. Various mixtures were prepared as noted in Table 3-4 and one specimen was cast for each mixture as specified by the standard. The change in height at 3, 7, 14, and 28 days with respect to the height at one day was measured using a micrometer.

Table 5-18 shows the percent change in height after 28 days with respect to the height at one day for the different mixers for Class C-1 grout. The measured percent change in height of the cylindrical specimens was less than 0.04% for all samples. This was close to the measuring limit of the micrometer. To determine whether the percent change in length is significantly different from zero a *t*-test was performed and the proposed null and alternate hypotheses for mean percent change in height (μ_i) are as shown in Equation 5.18:

$$\begin{aligned} &H_0 : \mu_i = 0 \\ &H_1 : \mu_i \neq 0 \ \text{ for at least one } i \end{aligned} \tag{5.18}$$

The last column of Table 5-18 shows the *p*-values of the t-tests performed and these *p*-values reveal that the null hypothesis at the 5% level of significance for both M1 and M2 mixer cannot be rejected. Hence the mean percent change in height of the cylindrical specimens is not significantly different from zero.

Table 5-18. Percent change in height and t-test for Class C-1 grout.

Mixer type	Mixture volume, ft^3 (m^3)	Mixture w/p	Percent change in height	t_0	*p*-value
M1	0.25 (0.007)	0.27	0.008	2.049	0.096
	0.25 (0.007)	0.30	-0.004		
	0.25 (0.007)	0.35	0.021		
	0.50 (0.014)	0.27	-0.004		
	0.50 (0.014)	0.30	0.038		
	0.75 (0.021)	0.30	0.029		
M2	0.25 (0.007)	0.27	0.000	2.010	0.115
	0.50 (0.014)	0.27	-0.004		
	0.50 (0.014)	0.30	0.021		
	0.50 (0.014)	0.35	0.033		
	0.75 (0.021)	0.27	0.021		

Similar hypotheses were formed for the C-2, C-3 and A grouts and the percent change in height for each mixture along with the t-statistics are shown in Tables 5-19, 5-20, and 5-21 for these grouts. The *p*-values for these grouts reveal that the mean percent changes in height of the cylindrical specimens are not significantly different from zero at the 5% level of significance.

Table 5-19. Percent change in height and t-test for Class C-2 grout.

Mixer type	Mixture volume, ft^3 (m^3)	Mixture w/p	Percent change in height	t_0	*p*-value
M1	0.50 (0.014)	0.25	-0.008	0.988	0.379
	0.50 (0.014)	0.26	0.017		
	0.50 (0.014)	0.30	-0.013		
	0.75 (0.021)	0.25	0.033		
	0.75 (0.021)	0.26	0.013		
M2	0.25 (0.007)	0.26	0.004	0.542	0.607
	0.25 (0.007)	0.30	0.000		
	0.50 (0.014)	0.25	0.004		
	0.50 (0.014)	0.30	-0.013		
	0.75 (0.021)	0.25	-0.004		
	0.75 (0.021)	0.30	0.000		

Table 5-20. Percent change in height and t-test for Class C-3 grout.

Mixer type	Mixture volume, ft^3 (m^3)	Mixture w/p	Percent change in height	t_0	*p*-value
M1	0.25 (0.007)	0.27	0.004	0.091	0.929
	0.50 (0.014)	0.27	-0.013		
	0.50 (0.014)	0.31	-0.004		
	0.75 (0.021)	0.26	0.003		
	0.75 (0.021)	0.27	0.011		
M2	0.25 (0.007)	0.26	-0.006	1.149	0.294
	0.25 (0.007)	0.31	0.000		
	0.50 (0.014)	0.26	0.004		
	0.50 (0.014)	0.27	-0.010		
	0.75 (0.021)	0.27	-0.002		

Table 5-21. Percent change in height and t-test for Class A grout.

Mixer type	Mixture volume, ft^3 (m^3)	Mixture w/p	Percent change in height	t_0	*p*-value
M1	0.25 (0.007)	0.42	0.006	0.066	0.949
	0.25 (0.007)	0.44	0.000		
	0.25 (0.007)	0.51	-0.017		
	0.50 (0.014)	0.42	0.002		
	0.50 (0.014)	0.44	-0.006		
	0.50 (0.014)	0.51	-0.013		
	0.75 (0.021)	0.42	0.015		
	0.75 (0.021)	0.44	-0.002		
	0.75 (0.021)	0.51	0.013		
M2	0.25 (0.007)	0.42	0.000	0.664	0.525
	0.25 (0.007)	0.44	0.000		
	0.25 (0.007)	0.51	0.000		
	0.50 (0.014)	0.42	0.004		
	0.50 (0.014)	0.44	0.004		
	0.50 (0.014)	0.51	0.008		
	0.75 (0.021)	0.42	0.000		
	0.75 (0.021)	0.44	-0.002		
	0.75 (0.021)	0.51	-0.006		

Although, the *t*-statistic test results indicate that there is no significant shrinkage or expansion for any of the four chosen grouts in this research, an interesting example shows that ignoring even a small shrinkage of 0.001 inch (25.4 μm) per 6 inch (153 mm) grout sample can lead to the substantial shrinkage in a PT duct. The resolution of the micrometer bridge used to perform the volume change test (ASTM C1090) is 0.001 inch. This means that shrinkage of 0.001 inch (25.4 μm) in a 6 inch (153 mm) cylindrical grout sample can be ignored by human error. Not let us consider that in a 150 ft (45.7 m) span PT duct, if the shrinkage of 0.001 inch is ignored then whereas it could be the actual shrinkage, then the total shrinkage in the 150 ft (45.7 m) PT duct is 3.6 inch (91.44 mm). Shrinkage of less than 2 inch (51 mm) is big enough to cause corrosion of strands. Hence by ignoring the shrinkage of 0.001 inch (25.4 μm) may lead to failure of the PT tendons and eventually the failure of the bride. It is therefore recommended that the resolution of Micrometer Bridge should be increased to measure the shrinkage smaller than 0.001 inch (25.4 μm).

5.3. Durability Characteristics

The results obtained from the chloride diffusion and pH tests are presented in this section.

5.3.1. Chloride Diffusion

The chloride diffusion tests were performed following ASTM C1556 test method as discussed in Section 3.3.7. Three samples for each grout were tested with the manufacturer's recommended w/p. The chloride diffusion coefficients obtained for the grouts mixed with the M1 and M2 mixers are shown in Table 5-22. The diffusion coefficient for the Class C-3 grout was the lowest followed by Class C-1 and C-2 grouts. The diffusion coefficient of Class A grout was found to be approximately six times higher than Class C grouts.

Table 5-22. Chloride diffusion coefficient results for all grouts.

Mixer	Grout	Diffusion Coefficient, D	
		ft^2/s	m^2/s
M1	Class A	7.00×10^{-11}	6.50×10^{-12}
	Class C-1	1.25×10^{-11}	1.16×10^{-12}
	Class C-2	2.86×10^{-11}	2.66×10^{-12}
	Class C-3	1.21×10^{-11}	1.12×10^{-12}
M2	Class A	-	-
	Class C-1	1.58×10^{-11}	1.47×10^{-12}
	Class C-2	1.89×10^{-11}	1.76×10^{-12}
	Class C-3	1.14×10^{-11}	1.06×10^{-12}

The chloride diffusion coefficient for high performance grouts is higher than the control grout (Class A grout). Assuming a ¼ inch (6.3 mm) clear cover for PT strands, the critical chloride threshold of 0.1% by weight of cementitious materials and the surface chloride concentration of 0.289% by weight of cementitious materials (Alonso et al. 2008), the time to initiation of corrosion for Class A and Class C grouts can be calculated using Equation 2.5. Note that this is only a comparative assessment and these times to corrosion are not representative of strands in PT bridges. The time to initiation of corrosion for Class A grout is 969 hours whereas it is 4771, 2849, and 5777 hours for the Class C-1, C-2, and C-3 grouts, respectively.

5.3.2. pH

The pH tests were performed following the test method described in Section 3.3.8. Three cylindrical specimens of 2-inch x 4-inch (51 mm x 102 mm) were initially cast to study the effect of mixer type on the pH of pore solution for all grouts. However, the pore solution extracted from one sample was not enough to measure pH value.

Therefore, three samples were used and the combined pore solution extracted by the three specimens was used to measure the corresponding pH values. Table 5-23 summarizes the pH values of the grout mixtures. Figures 5-19 and 5-20 show the pH values of the grout pore solutions when mixed with the M1 and M2 mixers.

Table 5-23. pH of pore solutions extracted from grout samples.

Mixer type	w/p	Grout type			
		Class A	**Class C-1**	**Class C-2**	**Class C-3**
M1	-5%	13.09	12.78	12.81	12.93
	Recommended	12.92	12.91	12.87	12.95
	+15%	12.94	12.87	12.74	*
M2	-5%	13.15	12.91	12.84	12.73
	Recommended	13.16	12.91	12.75	13.06
	+15%	12.58	12.98	12.86	12.91

* indicates test not performed for the particular mixture

Various research indicate that the corrosion of steel starts if the pH drops below a certain value because the passive oxide layer is destroyed at lower pH values. Mindess et al. (2003) mentioned that this passive oxide layer is destroyed if the pH of the pore solution drops below 11.5 and Locke (1986) mentioned a pH value to be 12. Assuming a more conservative case, the pH of the grout pore solution should be more than 12 for protection of strands from corrosion. The pH values for all grouts while mixing with the M1 and M2 mixers are well above 12. It is concluded that all Class C grouts used in this research perform better in corrosion protection of strands by carbonation.

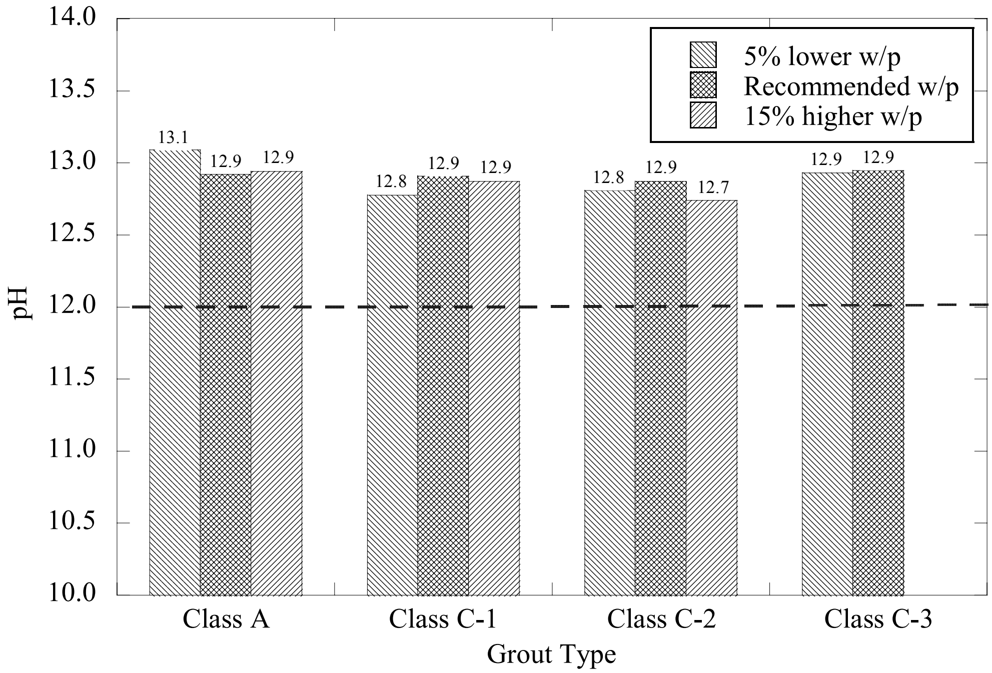


Figure 5-19. pH values of the pore solution of grouts mixed with M1 mixer.

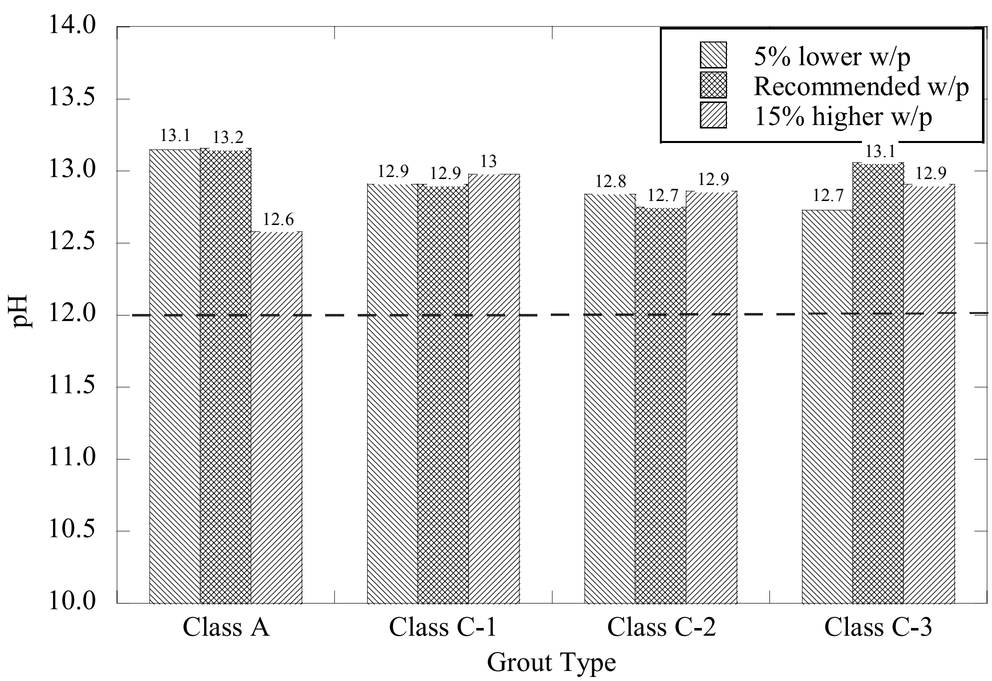


Figure 5-20. pH values of the pore solution of grouts mixed with M2 mixer.

5.4. Fillability

The fillability test was performed using the fillability meter. To study the repeatability of tests procedures, triplicates of fillability test was performed on four chosen grouts in study. The results obtained from the fillability meter are shown in the Figure 5-21 along with the standard deviation.

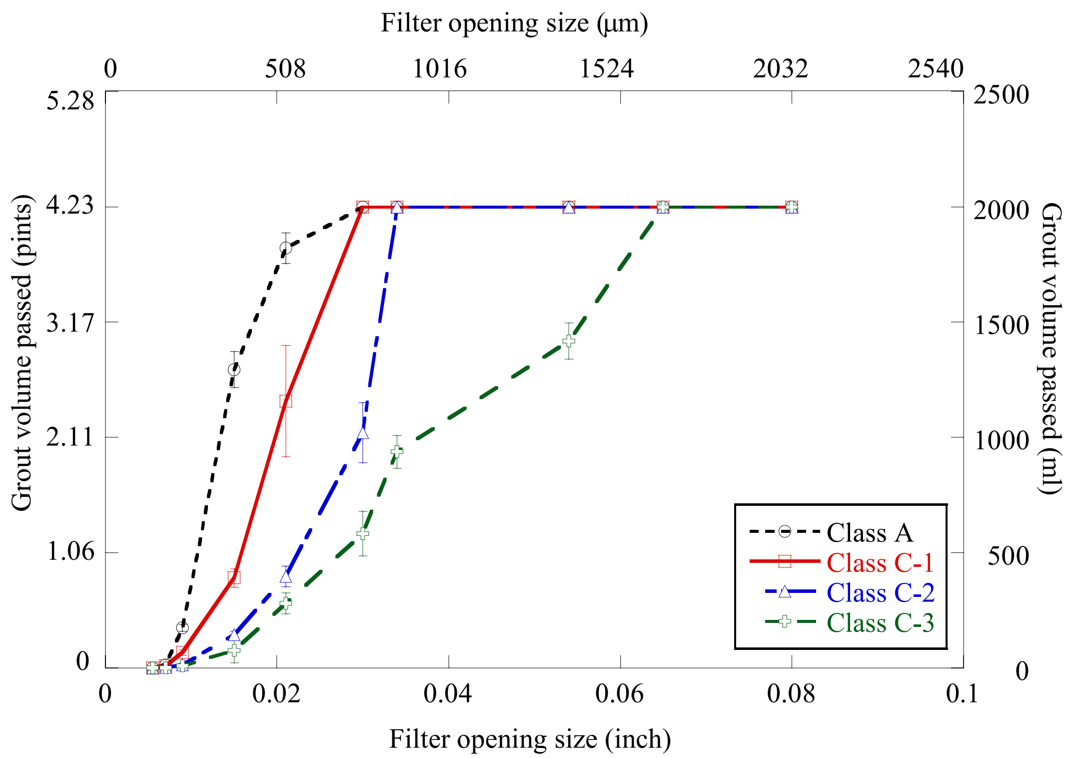


Figure 5-21. Fillability test results.

The results show that among three Class C grouts, the Class C-1 grout is more fillable when compared to the C-2 and C-3 grouts. The Class C-2 grout also exhibits fillability slightly lower than the Class C-1 grout. The Class C-3 grout did not perform well in terms of the fillability. Results indicate that the Class C-1 grout can easily pass through a 0.034 inch (864 μm) sieve opening. Results also indicate that 19.5% of the Class C-1 grout can flow through a 0.015 inch (381 μm) sieve opening whereas only 6.5% and 0.5% of Class C-2 and C-3 grouts passed through the same sieve opening before being clogged by the grout.

The fillability test results categorize the grouts based on their ability to pass through small voids. The fillability index was calculated using Equation 3.2. The fillability index calculations for Class A, C-1, C-2 and C-3 grouts are shown in Tables 5-24, 5-25, 5-26, and 5-27 respectively. The fillability index values from the test results are 3.3, 4.1, 5.3 and 7.5 respectively for Class A, C-1, C-2 and C-3 grouts. Lower values of the fillability indices indicate that the grout can "fill" smaller voids.

Table 5-24. Fillability index calculations for Class A grout.

Grout	Filter No.	Filter Size (inch)	Filter Size (μm)	Volume passed, pints (ml)	Percent volume passed	Percent volume retained (VRi)
Class A	#10	0.08	2032	4.227 (2000)	100	0
	#12	0.065	1651	4.227 (2000)	100	0
	#16	0.054	1372	4.227 (2000)	100	0
	#20	0.034	864	4.227 (2000)	100	0
	#24	0.03	762	4.227 (2000)	100	0
	#30	0.021	533	3.994 (1890)	94.5	5.5
	#40	0.015	381	2.916 (1380)	69	31
	#60	0.009	229	0.359 (170)	8.5	91.5
	#80	0.007	178	0.042 (20)	1	99
	#100	0.0055	140	0	0	100
				Fillability Index, FI =		**3.3**

Table 5-25. Fillability index calculations for Class C-1 grout.

Grout	Filter No.	Filter Size (inch)	Filter Size (μm)	Volume passed, pints (ml)	Percent volume passed	Percent volume retained (VR_i)
Class C-1	#10	0.08	2032	4.227 (2000)	100	0
	#12	0.065	1651	4.227 (2000)	100	0
	#16	0.054	1372	4.227 (2000)	100	0
	#20	0.034	864	4.227 (2000)	100	0
	#24	0.03	762	4.227 (2000)	100	0
	#30	0.021	533	2.938 (1390)	69.5	30.5
	#40	0.015	381	0.824 (390)	19.5	80.5
	#60	0.009	229	0.127 (60)	3	97
	#80	0.007	178	0.021 (10)	0.5	99.5
	#100	0.0055	140	0 (0)	0	100
					Fillability Index, FI =	**4.1**

Table 5-26. Fillability index calculations for Class C-2 grout.

Grout	Filter No.	Filter Size (inch)	Filter Size (μm)	Volume passed, pints (ml)	Percent volume passed	Percent volume retained (VR_i)
Class C-2	#10	0.08	2032	4.227 (2000)	100	0
	#12	0.065	1651	4.227 (2000)	100	0
	#16	0.054	1372	4.227 (2000)	100	0
	#20	0.034	864	4.227 (2000)	100	0
	#24	0.030	762	1.881 (890)	44.5	55.5
	#30	0.021	533	0.845 (400)	20	80
	#40	0.015	381	0.275 (130)	6.5	93.5
	#60	0.009	229	0.021 (10)	0.5	99.5
	#80	0.007	178	0 (0)	0	100
	#100	0.0055	140	0 (0)	0	100
					Fillability Index, FI =	**5.3**

Table 5-27. Fillability index calculations for Class C-3 grout.

Grout	Filter No.	Filter Size (inch)	Filter Size (μm)	Volume passed, pints (ml)	Percent volume passed	Percent volume retained (VR_i)
Class C-3	#10	0.08	2032	4.142 (1960)	98	2
	#12	0.065	1651	2.409 (1140)	57	43
	#16	0.054	1372	1.987 (940)	47	53
	#20	0.034	864	1.014 (480)	24	76
	#24	0.03	762	0.697 (330)	16.5	83.5
	#30	0.021	533	0.296 (140)	7	93
	#40	0.015	381	0.021 (10)	0.5	99.5
	#60	0.009	229	0 (0)	0	100
	#80	0.007	178	0 (0)	0	100
	#100	0.0055	140	0 (0)	0	100
				Fillability Index, FI =		**7.5**

Because three fillability tests were performed on all grouts, the fillability indices for all grouts along with their standard deviation in fillability index are shown in Table 5-28. The average fillability indices for Class A, C-1, C-2 and C-3 grouts are 3.39, 4.19, 5.21, and 6.73 respectively. The low values of standard deviation in fillability indices values show the repeatability of fillability test.

Table 5-28. Fillability indices along with the standard deviations for all grouts.

Grouts	Fillability Index				
	1	**2**	**3**	**Average**	**Standard deviation**
Class A	3.3	3.4	3.4	3.35	0.08
Class C-1	4.1	4.3	4.2	4.19	0.13
Class C-2	5.3	5.2	5.2	5.21	0.06
Class C-3	7.5	6.4	6.3	6.73	0.67

Based on the tests performed on the three Class C grouts and the Class A grout, the Class A grout possess higher fillability (indicated by lower fillability index). However, Class A grout bleeds due to which it cannot be acceptable for post-tensioning. Among the Class C grouts, Class C-1 grout was found to possess higher fillability when compared to the Class C-2 and C-3 grouts. Because all Class C grouts conformed to the TxDOT material specifications for grouts for post tensioning, any of the three grouts can be used for PT applications. However, Class C-1 grout was found to fill more voids when compared with Class C-2 and C-3 grouts. In general, a grout with low fillability index must be preferred for PT applications.

In an extension of this research, several laboratory tests were performed to grout the artificially voided ducts to suggest the repair strategies for the existing voided ducts. These tests were performed by Mr. Seok Been Im (a graduate student in the Civil Engineering Department at the Texas A&M University, College Station, TX). The length through which the repair grout travelled in the voided ducts was measured for all three Class C grouts. This length is defined as the infiltration length and is measured in feet. Table 5-29 shows the infiltration length valued for three Class C grouts along with their fillability indices.

Table 5-29. Fillability indices along with infiltration lengths.

Grouts	Fillability Index			Infiltration Length (ft)	
	1	2	3	1	2
Class C-1	4.1	4.3	4.2	15.0	14.5
Class C-2	5.3	5.2	5.2	14.4	14.3
Class C-3	7.5	6.4	6.3	3.9	-

Because the fillability indices and infiltration length datasets were not of the same size (in terms of the number of observations), hence a many-to-many relationship between the fillability index and infiltration length was formulated and is shown in the Figure 5-22.

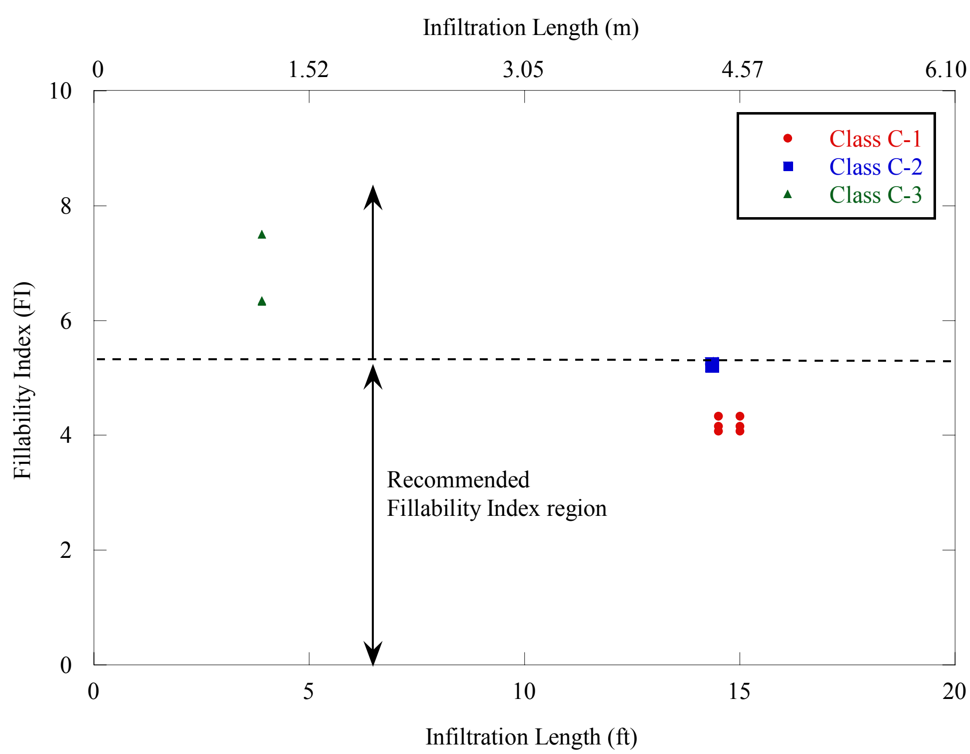


Figure 5-22. Relationship between fillability index and infiltration length.

Based on the relationship obtained between the fillability index and infiltration length, it is observed that Class C-1 and C-2 grouts has fillability index values below 5.3 and the infiltration length above 14.3 ft. Based on the above results, it is recommended that the grouts with a fillability index of 5.5 or less are good for the repair purposes. On the other hand, grouts with a fillability index above 5.5 are not recommended for repair grouting and further research is needed to evaluate their grout characteristics.

5.5. Summary of Results

A summary of various grout characteristics evaluated in this research for Class A, C-1, C-2, and C-3 is presented in Table 5-30. The values shown in the Table 5-30 are overall mean values obtained in the test program.

Table 5-30. Summary of the test results obtained for each grout characteristic.

Grout Characteristic	Class A	C-1	C-2	C-3
Wick-induced bleed, %	2.05	0	0	0
Fluidity (immediately after mixing), seconds	4.95	10.32	13.03	9.99
Viscosity (immediately after mixing), Poise (Pascal.seconds)	42.53 (4.25)	-	17.09 (1.71)	106.96 (10.70)
Wet density, lb/gal (g/cm^3)	15.62 (1.87)	17.57 (2.11)	17.55 (2.10)	16.35 (1.96)
Initial setting time, hours	4.81	5.12	9.34	9.47
Compressive strength, ksi (MPa)	6.84 (47.18)	11.24 (77.48)	11.57 (79.77)	9.17 (63.22)
Volume change, %	0	0	0	0
Chloride diffusivity (10^{-11}), ft^2/s (m^2/s)	7.00 (0.65)	1.42 (0.13)	2.38 (0.22)	1.18 (0.11)
pH	13.04	12.91	12.81	13.01
Fillability, FI	3.35	4.19	5.21	6.73

Based on the experimental results, grout characteristics that meet the current TxDOT specification DMS-4670: Grouts for post-tensioning were evaluated for each grout and the results are presented in Table 5-31. Table 5-31 indicates that the Class C grouts (C-1, C-2, and C-3) met the current TxDOT grouting specifications, whereas Class A grout did not met the current specifications. It is also noted that the three Class C grouts are seemingly good for grouting PT ducts according to the current TxDOT specifications. However, the current specifications do not well characterize the Class C grouts. Therefore, it is difficult to determine which grouts can fill voids efficiently to prevent voids and corrosion of the strands. The requirements for grouts shown in Table 5-31 require modification and additional tests should be included to better characterize the grouts.

Table 5-31. Grout characteristics that met current DMS-4670 specifications.

Grout Characteristic	**Class A**	**C-1**	**C-2**	**C-3**
Wick-induced bleed	×	√	√	√
Fluidity (immediately after mixing)	×	√	√	√
Viscosity (immediately after mixing)	NR	NR	NR	NR
Wet density	NR	NR	NR	NR
Initial setting time	√	√	√	√
Size gradation	√	√	√	√
Compressive strength	√	√	√	√
Volume change	√	√	√	√
Chloride diffusivity	NR	NR	NR	NR
pH	NR	NR	NR	NR
Fillability, FI	NR	NR	NR	NR

√ indicates grout meet current DMS-4670 specifications

× indicates grout did not meet current DMS-4670 specifications

NR indicates grout characteristic not required in current DMS-4670 specifications

6. PROPOSED SPECIFICATIONS

The current TxDOT specifications for PT grouting applications are contained in DMS-4670, *Grouts for Post-Tensioning.* Research indicates that these specifications should be modified. The requirements for maximum particle size gradation should be modified. The requirements for two grout characteristics, fluidity and initial setting times, should be modified. Also, two new test methods, the wet density and fillability test, should be added to the current specifications. The following pages show the newly proposed modified DMS-4670 specifications. The additions to this specification are underlined and all requirements that have been removed should have been struck through.

TxDOT's modified material specification for selection of grouts for post-tensioning is shown on the following pages with suggested modifications based on findings from this research (TxDOT 2004).

6.1. Modified DMS-4670 Specifications

DMS-4670, Grouts for Post-Tensioning[1]

Overview

Effective Date: August 2004 (New Specification).

This Specification governs for the prequalification procedure, packaging, and material properties of thixotropic grouts for post-tensioning.

Material Producer List

The Materials and Pavements Section of the Construction Division (CST/M&P) maintains the list of qualified manufacturers of thixotropic grouts for post-tensioning. Only manufacturers of thixotropic grouts for post-tensioning on the Material Producer List can be used on Department projects.

The Department reserves the right to conduct random sampling of materials from prequalified manufacturers for testing and to perform random audits of documentation. Department representatives may sample material from the manufacturing plant, the project site, and the warehouse. CST/M&P reserves the right to test samples to verify compliance with this Specification.

Prequalification Requests

To prequalify material, submit a letter to the Texas Department of Transportation,

Construction Division, Director of the Materials & Pavements Section (CP51), 125 East 11th Street, Austin, Texas 78701-2483, and include the following:

- company name
- physical and mailing address and
- contact person and phone number.

[1] Source: TxDOT 2004

Prequalification Requirements

Manufacturers requesting prequalification must meet the following requirements.

- Test all grouts with results meeting the minimum material requirements of this Specification.
- Provide an independent laboratory test report from a laboratory audited and inspected by the Cement Concrete Research Laboratory, certifying compliance of the material to this Specification.
- Submit a minimum of one bag of grout for testing to the Texas Department of Transportation, Construction Division, Materials and Pavements Section (CP51), 9500 Lake Creek Parkway, Austin, Texas 78717.

All materials submitted for prequalification tests are at no cost to the Department.

Packaging and Labeling

Prepackage grout in plastic lined or coated bags. Grout bags must indicate the brand name, date of manufacture, lot number, and mixing instructions. The grout supplier must provide the Contractor and Engineer with a copy of the quality control data sheet for each lot number and shipment sent to the jobsite.

Material Properties

No grout may contain:

- aluminum powder
- gas generating components that produce hydrogen gas, carbon dioxide, or oxygen
- expansive admixtures or
- admixtures containing chlorides.

The grout must meet the material requirements stated in the following table.

Material Requirements of Grout

Property	Requirement	Test Method
Total Chloride Ions	Maximum 0.08% by weight of cementitious material	ASTM C1152
Fine Aggregate (if used),	Gradation Maximum Size ≤ No. ~~50~~ 100 Sieve	Tex-401-A
Volume Change	0.0% to 0.1% expansion at 24 hr. and 0.0% to 0.2% at 28 days	ASTM C1090[1]
Bleeding	Maximum 0.0% at 3 hr.	Tex-441-A (see *Note*)
Compressive Strength (Average of 3 cubes)	>3000 psi at 7 days and >5000 psi at 28 days	Tex-442-A (see *Note*)
Initial Set of Grout	Minimum ~~3~~ 4 hr., Maximum 12 hr.	ASTM C953
Fluidity - Efflux Time from Flow Cone: (a) Immediately after mixing (b) 30 min. after mixing with remixing for 30 sec.	Minimum ~~9~~ 5 sec., Maximum 20 sec. Maximum 30 sec.	Tex-437-A Method 2
Permeability at 28 days	Maximum 2,500 Coulombs; At 30 V for 6 hr.	ASTM C1202[2]
Wet density	$\rho_{\text{observed}} = \rho_{\text{predicted}} \pm 0.31$ where $\rho_{\text{predicted}} = -28.4 + 104.6\,(\text{w/p}) + 2.1\left(\rho_{\text{dry}}\right)$	Baroid mud balance
Fillability	FI ≤ 5.5	Fillability test

[1]Modified to include verification at only 24 hr. and 28 days.
[2]Moist cure specimens at 73°F ±3°F for 26 days. At 26 days, condition water, cut specimens to size, and dry and coat sides with epoxy gel. At 27 days, place prepared samples under vacuum as per method. Test at 28 days.
Note: Contact CST/M&P for more information regarding this test method.

Disqualification

Any change in cement or admixtures of a particular grout may result in removal from the MPL and disqualification for Department use. The material must be requalified for acceptance.

The manufacturer may resubmit their product for requalification consideration, after following the procedures stated in 'Prequalification Requirements.'

End of Specification DMS-4670, Grouts for Post-Tensioning

The current specifications requires that the pre-packaged PT grouts will qualify for post-tensioning applications only if they do not contain either aluminum powder, gas generating components that produce hydrogen gas, carbon dioxide, or oxygen, expansive admixtures, or admixtures containing chlorides. The grouts containing gas generating components are disqualified because these grouts may result in the formation of entrapped voids due to generation of gases. Grouts with expansive admixtures are disqualified because the grout expansion may result in the cracking of HDPE ducts, which can lead to durability issues. Addition of aluminum powder also contributes to the expansion by liberating hydrogen gas which can form voids within the grout which could also result in durability issues. Therefore, grouts with aluminum powder are disqualified.

The addition of two new tests, the wet density test and the fillability test, in the current DMS-4670 specifications, is technically justified based on this research. It is also important to justify the impact of these additional tests on the overall project costs, and whether the costs associated with these tests are significant. Consider that a quality control inspector can perform the wet density test in the field once for each grout mixture prepared. The fillability test, on the other hand, needs to be performed in the laboratory before selecting the grout for post-tensioning.

The total cost associated with these tests should conservatively be less than $5,000 for repair of an existing PT bridge. Because this cost is small it can be ignored when comparing it with the overall project cost, which can be of the order of several million dollars. Therefore, allocating a minimal budget to ensure better fillability and durability of the grout is certainly justified.

Table 6-1 shows grout characteristics that met the modified TxDOT specification DMS-4670 for Class A, C-1, C-2, and C-3 grouts. Note that all grouts met the requirements of the current TxDOT specifications. However, according to the modified DMS-4670 specification, only Class C-1 and C-2 grouts qualify for the grouting of new PT structures and for repair of existing PT structures. Class C-3 grout did not exhibit good fillability. It also contained fine aggregates with maximum particle size larger than 150μm (No. 100 Sieve) which could clog the flow of grout through small openings and result in more voids. This was confirmed with actual repair of ducts.

Table 6-1. Grout characteristics that met the modified DMS-4670 specifications.

Grout Characteristic	Class A	C-1	C-2	C-3
Wick-induced bleed	×	√	√	√
Fluidity (immediately after mixing)	×	√	√	√
Viscosity (immediately after mixing)	NR	NR	NR	NR
Wet density	√	√	√	√
Initial setting time	√	√	√	√
Gradation maximum size	√	√	√	×
Compressive strength	√	√	√	√
Volume change	√	√	√	√
Chloride diffusivity	NR	NR	NR	NR
pH	NR	NR	NR	NR
Fillability	√	√	√	×

√ indicates grout meet modified DMS-4670 specifications

× indicates grout did not meet modified DMS-4670 specifications

NR indicates grout characteristic not required in modified DMS-4670 specifications

7. CONCLUSIONS

The current TxDOT specifications for grouts provide test methods and threshold values for cement grouts. These standards fail to provide specifications to test pre-packaged proprietary cementitious-based grouts for the ability of a particular grout to fill voids. Also, some TxDOT recommendations (desirable limits of efflux time) may not be appropriate.

Significant voids have been found in ducts in a number of PT bridges in Texas constructed before year 2000. These bridges may require repair of the voided PT ducts by filling with a suitable grout. All three prepackaged Class C grouts evaluated in this research conformed to the current TxDOT grout specifications. These grout exhibited zero bleed, limited shrinkage, and good fluidity. However, grout C-3 exhibited poor fillability.

The Class C grouts exhibited a slow increase in the viscosity over time. This is likely due to the delayed hydration or retardation of these grouts. Characterization of pre-packaged grouts is very important as it provides ample time for material engineers to assess applicability of these pre-packaged grouts.

The effects of mixer type, mixture volume, and w/p on the grout characteristics were evaluated to determine the sensitivity of each grout due to the change in these factors. It was found that the fluidity and viscosity were, to some extent, affected by the change in mixer type. Two mixers with different rotating speeds were used and the mixer with the higher rpm (M2 mixer) resulted in better fluidity of the grouts.

Three different mixture volumes were evaluated in this research to study the effect of the mixture volume on a grout's fresh characteristics. The fluidity and viscosity were the two main characteristics affected by the change in mixture volume. As the mixture volume increased the fluidity decreased lower volumes resulted in grouts with lower viscosity values. However, no significant change in the grout's fluidity was observed with the change in mixture volume for any of the grouts studied at a 5% level of significance.

The sensitivity of w/p was also evaluated in this research. As expected, the fluidity of all grouts increased as the w/p increased. This increase in fluidity was due the increase of water content of the mixture. Viscosity and density also decreased with an increase in w/p.

The newly developed fillability test procedure is found to be a useful procedure in differentiating the pre-packaged PT grouts in terms of their void filling ability. The fillability test results indicate that Class C-1 and C-2 grouts performed well in terms of their void filling ability with a fillability index less than 5.5. The Class C-3 grout resulted in a higher fillability index (> 5.5) indicating that it will not fill small voids efficiently. The fillability test procedure can assist constructors and engineers in determining a suitable pre-packaged PT grout for use in post-tensioning, either for new or repair scenarios.

Testing from this research indicates that the following changes to the current DMS-4670 specifications should be made:

- The maximum size fine aggregates allowed in a PT grout should be reduced from No. 50 Sieve (300 μm) to No. 100 sieve (150 μm).
- The minimum efflux time should be lowered from 9 seconds to 5 seconds when grouting is performed with a positive head (i.e., when grouting is done from the lowest duct elevation.
- The minimum initial setting time is increased from 3 hours to 4 hours. Although an increase in the initial setting time does not increase the workability time, it may provide a grout mixture with better fillability.
- The wet density test using a Baroid mud balance should be required for all grouting of PT ducts. The wet density value determined in the field should be within the limit shown in the Equation 5.12.
- The fillability test developed in this research should be used to assess the fillability of grouts. The fillability index should be less than or equal to 5.5.

This research provides recommendations to modify the current TxDOT specifications for PT grouts (DMS-4670 Grouts for Post-tensioning) such that high-performance grouts can be objectively assessed and grouts that can fill voids more efficiently must be selected for grouting PT ducts. The recommendations made in this research will improve the durability of PT structures and will enable safe repair and construction of PT bridges.

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APPENDIX A: MATERIAL CHARACTERIZATION TEST PROCEDURES

A.1 Viscosity Measurements using the DV-III+ Programmable Rheometer from Brookfield Engineering

(Prepared by Michael Gamble, former graduate student at the Texas A&M University, Portions obtained from Brookfield Assembly Instructions and the Brookfield Digital Rheometer Model DV-III+ Operating Instructions Manual No. M/98-211-A0701)

1. Read all directions before performing the viscosity measurements.
2. Personnel, material, and equipment requirements:
    a. One person
    b. DV-III+ Programmable Rheometer from Brookfield Engineering
    c. Model D Helipath™ Stand from Brookfield Engineering
    d. Computer Program - Rheocalc V2.4 or newer version
    e. Appropriate computer to run the computer program and connect to the rheometer
    f. Cement
    g. Water
    h. Scoop
    i. Balance – accurate to at least ± 0.01 g
    j. Black cylinder molds – 4"x 8" for testing

k. Tape – Scotch Magic™ Tape will work

l. Small beaker – 500 ml or 1000 ml to help clean the spindle and temperature probe after each test

m. Paper towels

3. Assembling the Helipath™ Stand

   a. Remove the screw and washer from the upright rod.

   b. Place the rod and clamp assembly into the hole in the top of the base.

   c. Rotate the rod/clamp assembly slightly until the slot on the bottom of the rod intersects the pin located in the base.

   d. While holding the rod and base together, insert the slotted screw and washer and tighten securely.

4. Mounting the DV-III+ to the Helipath™ Stand

   a. Insert the viscometer mounting rod on the back of the DV-III+ into the hole (with the cut away slot) in the clamp assembly.

   b. Check the lateral position of the viscometer relative to the base.

   c. Make adjustments and retighten the screw as required to center the viscometer between the base legs.

   d. Referring to the stand bubble level, adjust the base leveling screws until the stand is level.

   e. Adjust the instrument level until the bubble is centered from right to left and tighten the clamp knob (clockwise).

f. Use the leveling screws to “fine” adjust the viscometer level. (Caution: Position power cords so they do not interfere with the travel of the drive unit.)

5. Turn the DV-III+ power switch on. The switch is located on the right backside of the base unit.
6. Once the DV-III+ is turned on, you can open the Rheocalc program on the computer. Rheocalc V2.4 was used for this study.
7. The screen on the DV-III+ will read as follows:

Brookfield
DV-III+ Rheometer
1 = EXTERNAL CONTROL
2 = STANDALONE MODE

Press the control key, 1, on the face of the DV-III+ Rheometer for external control through the computer.

8. The Rheocalc program will start on the Dashboard page. On this page you must select which spindle to use. There is a pull down menu under the heading Spindle that allows you to select which spindle is being used. Spindle T-A (#91) will be used for the tests.
9. Zeroing the Rheometer

a. Before readings may be taken, the rheometer must be autozeroed. It is important to let the rheometer warm up for about 10 minutes before zeroing the machine.

b. The Zero button is in the lower left hand corner of the Dashboard page.

c. The rheometer must be zeroed while the unit is balanced and before the spindle is attached. The unit can be balanced by using the leveling screws on the bottom of the base stand. Once the Zero button is pressed, a Warning message will appear on the computer screen:

d. Rheometer will now be zeroed. Please ensure the rheometer is level and the spindle is removed.

e. Click on the zero button and allow approximately 15 seconds for the rheometer to zero.

10. Attaching the Spindle

a. Select a T-bar spindle.

b. Attach the weight to the closer piece of the chuck assembly.

c. Slide the spindle through the weight and closer into the chuck and tighten before attaching the chuck to the viscometer.

d. Connect the chuck/closer/weight assembly, with spindle, to the viscometer.

11. Grout Sample

a. After completion of mixing, collect grout sample in a 4”x 8” cylinder mold.

b. This is an appropriate size container for the spindle to spin freely in the grout mixture while not touching the sides of the container.

c. The sample can now be taken to the Brookfield Rheometer.

12. Test Setup

a. Once the grout is in the testing cylinder, the temperature probe can be taped to the inside of the container right above the grout level.

b. Then place the container under the rheometer.

c. If the rheometer is high on the stand and the spindle is not in the grout, lower the spindle into the grout by depressing the disengaging lever on the Helipath™ drive unit.

d. The recommended initial spindle immersion is when the cross-bar of the T spindle is ¼” below the surface of the grout.

e. At this time the reversing rod on the drive unit should be pushed down. Make sure that the drive unit is OFF (the light on top of the drive unit will not be illuminated).

f. Set the adjustable stops to accommodate the travel of the Helipath™ that will provide the desired penetration of the spindle (recommended 1-1/2”). The top stop should be lowered to the top of the drive unit so that the drive unit will not move any higher and thus raise the cross-bar of the T-spindle to where it has less than ¼” of material above it.

g. The testing can then be started at five minutes after the completion of mixing, or any other appropriate time while the grout is still in its fluid state. When the program is started the Helipath™ drive unit should be turned on also (the light on the drive unit will now be illuminated.

13. Test Program

a. Click on the Programs tab in the Rheocalc program.

b. The written program that was used for this test was as follows:

SSN 010.

DCI 00:15

WTI 15:00

c. This means that the rheometer will be set to a rotational speed of 10 rpm and that it will record data every 15 seconds for 15 minutes.

d. The progress of the program can be viewed on the Programs tab or the measurements can be seen continuously on the Dashboard tab.

14. Data Collection

    a. Once the program has run completely, the collected data will be shown on the View/Edit tab. On this tab, you can save, print, and export to an Excel file the collected data.

    b. The data can also be plotted. Click on the Plot tab and print out a plot using any of the recorded variables.

15. Test Cleanup

    a. When the test is completed, turn the Helipath™ drive unit off.

    b. Depress the disengaging lever on the Helipath™ drive unit to raise the spindle out of the grout.

        a. The drive unit will come into contact with the upper adjustable stopper before the spindle is removed from the grout. The adjustable stopper can be raised so that the spindle is out of the grout, but if several comparable tests are being run, the adjustable stoppers should probably not be moved so that each test will be confidently the same. If this is the case, the spindle can be lifted at an angle to a height in which the container holding the grout can be removed from under the Helipath™ stand.

        b. The temperature probe can be removed from the container and then the container can be discarded appropriately.

        c. It is important to thoroughly clean the temperature probe and the spindle with water and paper towels right after each test. If the spindle is not cleaned completely after each test, grout deposits remaining on the spindle would result in larger torque % readings and thus a larger and erroneous viscosity measurement.

16. Report

    a. Date and identification number of the test specimen

    b. Identification of the test equipment and instruments used

c. Written program used and the start time of the test from the addition of water to the grout

d. Any deviation from the test method together with other information of importance

e. A plot showing the measured viscosity versus time and temperature versus time

A.2 Procedure determine representative dry density of grout powder using Baroid mud balance

1. Read all directions before performing the dry density test.
2. Personnel, material, and equipment requirements:
    a. One person
    b. Baroid mud balance
    c. One ½ liter scoop
    d. Grout powder
    e. Tamping rod (12” long)
3. Test procedure
    a. Open one grout bag and take approximately 1 lb (454 g) of grout powder in a ½ liter scoop.
    b. Place Baroid mud balance base stand on a level surface.
    c. Pour grout powder in the balance cup and fill it to approximately half of the total volume. Once the balance cup is half filled, tap it 10 times using the tamping rod to ensure sufficient compaction.
    d. After tapping, add more grout powder to fill it upto the top. Tap the mud chamber again 10 times.
    e. Add a little extra powder to overfill the mud chamber. Using tamping rod, scrap the extra grout powder from the mud balance to level the top surface.
    f. Place the balance arm on the fulcrum and then place the lid over the balance cup in inverted position.

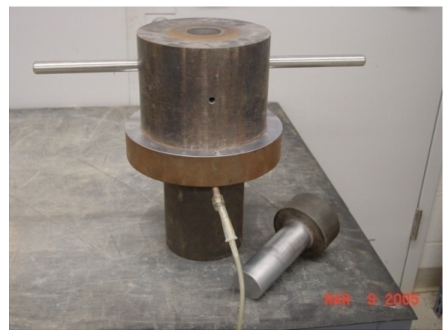
g. Balance the assembly by moving the rider along the arm. Take the reading from the balance arm when the mud balance is horizontal. Report the reading to the nearest 0.1 lb/gal (0.01 g/cm^3).

4. Repeat step 3 for three different bags of grout and report the final grout dry density by averaging the three obtained density values.

A.3 Procedure for pH Test of the Pore Solution of Grout

(Obtained from *Expression and Analysis of Pore Fluids from Hardened Cement Pastes and Mortars* by R.S. Barneyback, Jr. and paper from Dr. Zollinger's student Shon)

1. Read all directions before performing the viscosity measurements.
2. Personnel, material, and equipment requirements:
    a. One person
    b. Pore Fluid Expression Device – consisting of support cylinder, platen, die body, and piston assembly



    c. Small rubber hose
    d. Disposable plastic syringe
    e. 6 mm thick Teflon seal – inserted between the top of the specimen and the bottom surface of the piston
    f. 2”x 4” black plastic cylindrical molds with top
    g. Tinius Olsen Compression Machine
    h. Plastic pipettes
    i. Denver Instrument Company – Model 250 pH/Ion/Conductivity Meter (any of the other models, Model 215, 220, 225, would also be sufficient)
    j. Plastic bags
3. Sample Preparation
    a. Once the grout has been mixed, fill 4 of the 2”x 4” plastic molds with the grout.

b. Close the containers with the provided tops so that moisture is not allowed to escape.

c. Label the different specimens.

d. Store these specimens together in a constant temperature environment.

e. After initial set, remove the specimens from their molds and leave them in curing environment.

4. Test Setup

a. Place the support cylinder on the lower bearing surface of the compression machine.

b. At this time, check the platen for any debris in the fluid drain or area where the test specimen will be placed.

c. Once the platen has been cleaned appropriately, place the platen on top of the support cylinder so that the support cylinder fits into the provided grooves on the bottom of the platen and so that the fluid drain is accessible.

d. Two designs can be used at the fluid drain. A small rubber hose can be pushed up into the drain hole to receive the fluid or a small threaded pipe can be screwed into the drain with some Teflon tape wrapped around the threads. With this setup, the rubber hose can be fitted to the end of the small pipe.

e. A small plastic disposable syringe without the needle can be fitted into the end of the rubber hose to later retrieve the water.

f. Spray a thin coating of film-bonding grade fluorocarbon over the mating surfaces of the die body and platen, over the bore of the die body, and the shaft of the piston.

g. The die body can then be centered in the grooves on the upper surface of the platen.

5. Pore Solution Collection Procedure

a. Make sure your test apparatus is completely set up in the compression machine.

b. Take one of your samples and remove it from its plastic mold. The container may have to be cut if the specimen will not slide out.

c. The specimen should be placed directly into the bore of the die body. If the specimen is already removed from its mold, it should be retrieved from the curing environment and promptly placed in the mold. This will reduce its exposure to ambient air.

d. Place the 6 mm thick Teflon seal on top of the specimen

e. Then place the piston assembly in the bore on top of the Teflon seal and test specimen

f. The piston should then be loaded at a rate equivalent to a compressive stress increase of about 2.8 MPa/s (about 400 psi/s)

g. The rate should increase until the maximum pressure of 540 MPa is reached or a sustained pressure that allows for the collection of a sufficient quantity of pore fluid (3 to 4 ml) in a plastic syringe through the fluid drain

h. The plunger on the plastic syringe should be pulled out a short distance to put a slight negative pressure on the pore fluid drainage system

i. It is also helpful to temporarily withdraw the syringe from the rubber hose to allow some of the accumulated gases to escape from it several times during each test

j. If sufficient pore fluid is not collected on this first cycle, the pressure should be reduced to about 350 MPa to allow some elastic rebound to occur. On increasing the pressure back to the maximum level additional pore fluid can be withdrawn into the syringe. This can be repeated for several steps, but it is seldom possible to recover more fluid after 3 or 4 times.

k. It is important to avoid undue exposure of the pore solution to air. It should be sealed in a plastic container until the time of analysis.

6. pH Analysis

a. Once 2 to 3 ml of pore solution is collected in the syringe, the solution can be transferred into a small container that will receive a pH glass electrode. (We will use a plastic pipette that has the shaft end cut off. This can be seen in Figure 8.2.)

b. Hold the plastic pipette half under the pH glass electrode.

c. The initial reading on the pH meter is the desired reading. The pH reading will drop after this initial reading due to the exposure to air.

d. This test can be performed at 1, 7, 14, and 28 days

7. Cleaning the test apparatus

a. It is necessary to disassemble the apparatus, recover the remolded specimen, and clean all surfaces immediately after recovery of the expressed fluid

b. The die body is removed from the platen and the platen surface and its drain system are flushed with absolute ethanol and wiped clean with soft facial tissue at least twice, and until no residue remains

c. After the platen is cleaned and the fluid drain is flushed, it can be removed from the top of the support cylinder

d. If the remolded specimen is too tightly packed into the die body, the die body should be placed onto the support cylinder, the piston cap removed from the piston, and pressure is applied to the top of the piston to eject the remolded specimen from the bore into the central opening of the support cylinder

e. The apparatus can be disassembled and the specimen recovered and sealed in a plastic bag for storage or further analysis

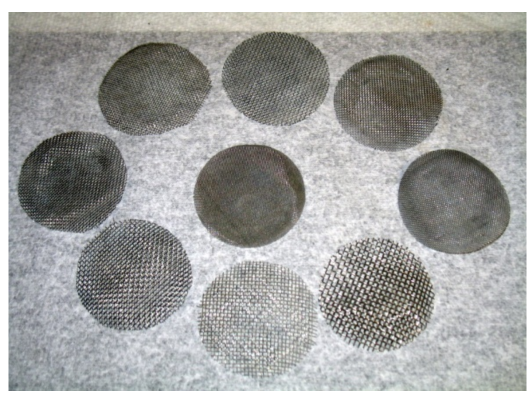
f. The piston and die are cleaned using absolute ethanol and facial tissue until all residual material is removed

g. All surfaces are then recoated with a fresh coating of fluorocarbon

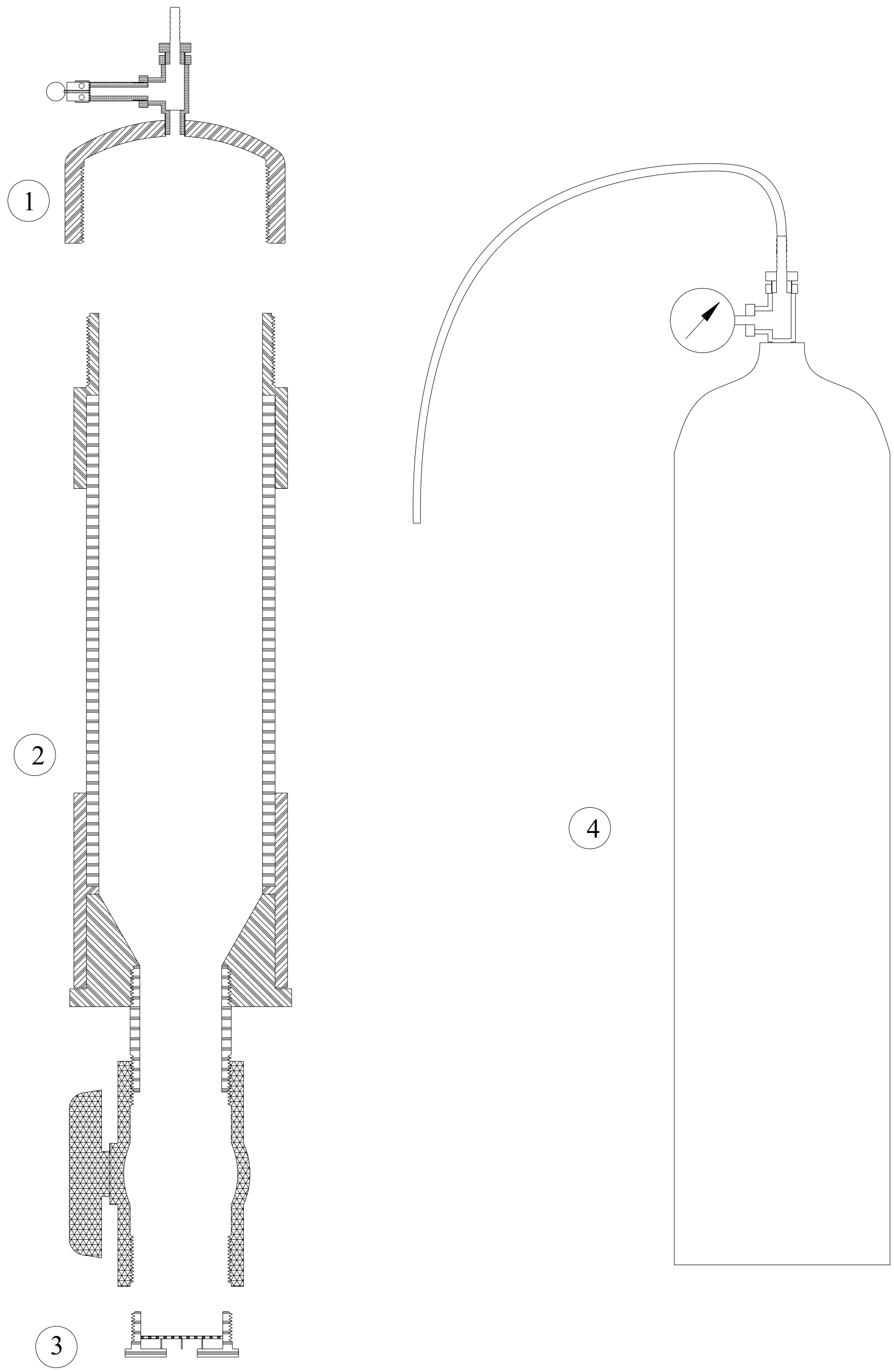
A.4 Procedure for fillability Test of Grout

(Developed in laboratory based on the penetrability meter developed by Eriksson and Stille)

1. Read all directions before performing the fillability test.
2. Personnel, material, and equipment requirements:
    a. One person
    b. Fillability meter developed in laboratory by PVC schedule 40 and schedule 80 fittings, including different size stainless steel screen filters
    c. Pressurized nitrogen gas cylinder assembly
    d. One 2 liter scoop and four 1000 ml graduated cylinders
    e. One stop watch
    f. Wire mesh (< ¼ inch clear opening)
3. Sample preparation



    a. Prepare the grout by mixing a known amount of grout with a known amount of water based on the mixture proportions
    b. Mix the grout for 5 minutes unless otherwise mentioned in the mixing procedure



Fillability meter parts:
1. Top cap with attached barbed hose adapter for connecting with air supply
2. Grout vessel with 2 inch (51 mm) valve at hte bottom to control the flow of grout through filter.
3. Male pipe thread plug with filter.
4. Pressurized air supply cylinder.

c. Immediately after the mixing, perform the flow cone test on the grout mixture and note the efflux time

d. Affix the fillability meter grout vessel (part number 2) on the table near the pressurized air supply

e. Place a filter in the male pipe thread plug (part number 3) and screw it at the bottom end of the grout vessel

f. Close the 2 inch grout valve attached to the grout vessel at the bottom

g. Measure 2000 ml (= Total volume,V_T) of grout in the scoop and pour it in the fillability meter

h. Close the fillability meter from the top by using the top cap with affixed barbed hose adapter (part number 1) and connect the hose with the barbed hose adapter.

i. Put a protective wire mesh cover on the fillability meter to protect any damage

4. Test setup

   a. Place a 2 liter graduated beaker below the fillability meter bottom outlet to collect the grout

   b. Once the fillability meter is covered with protective wire cage, open the pressure cylinder valve and maintain a constant pressure of 20 psi (0.138 MPa). The grout will now start flowing out of the bottom outlet under the pressure. Let the grout flow under this pressure

   c. Measure the volume of grout collected in the beaker once no more grout flows. Note down the volume of grout against the filter size in the observation table as shown in the Table A.4 below

d. Stop pressure supply when no further grout flows through the bottom outlet or no grout left in the meter. Release air pressure, remove the air supply and clean the fillability meter and filter immediately

5. Repeat steps 4 and 5 for different filter sizes for all three grouts in study and measure the volume of grout passing each filter. Calculate the percent volume passed, percent volume retained on each filter, and the fillability index as shown in the Table A.4 below

6. Plot a graph between the filter size and volume of grout passed for the three thixotropic grouts under study. Compare the filling ability of each grout

Table A.4. Observations record.

Grout	**Filter No.**	**Filter Size (inch)**	**Filter Size (μm)**	**Volume passed, pints (ml)** **(V_P)**	**Percent volume passed** **($\%V_P = V_P/V_T*100$)**	**Percent volume retained** **($VR_i = 100-\%V_P$)**
Grout Class	#10	0.08	2032	4.23 (2000)	100	0
	#12	0.065	1651	4.23 (2000)	100	0
	#16	0.054	1372	...		
	#20	0.034	864	...		
	#24	0.03	762	…		
	#30	0.021	533	…		
	#40	0.015	381	…		
	#60	0.009	229	…		
	#80	0.007	178	…		
	#100	0.0055	140	…		

Total Volume, V_T = 2000 ml **Fillability Index, FI = $\Sigma VR_i/100$**

VITA

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